VŠB– Technical University of Ostrava
Faculty of Electrical Engineering and Computer Science
Department of Electronics

Design of Transformer with High Current Output and Voltage Drop Compensation

Návrh proudového transformátoru s kompenzací úbytku napětí

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2. Do the design of transformer with high current output acording to requirements of laboratory measurement of electrical apparatus
3. Check the analytic design of transformer by FEM simulation
4. Find the method of compensation of output voltage drop
5. Apply the selected compensation method into your design of transformer
6. Conclusion

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I hereby declare that this master's thesis was written by myself. I have quoted all the references I have drawn upon.

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Ostrava, May 14, 2020 ....

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R Thiyagu

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Abstract

The concept is to design a single phase transformer with high current output according to requirements of laboratory measurements. The theoretical background and types of transformer are explained. Analytical calculation to design a transformer is calculated. The finite element model is designed with the help of analytical calculation and a regulation method is found to compensate the output voltage drop. The regulation method is designed and used in the design of transformer. The model is checked by FEM simulation.

Keywords: Transformer, Construction, Simulation, Single phase transformer, Regulation.

Abstraktní

Cílem je navrhnout jednofázový transformátor s vysokým proudovým výstupem podle požadavků laboratorních měření. Jsou vysvětleny teoretické základy a typy transformátorů. Vypočítá se analytický výpočet pro návrh transformátoru. Model konečných prvků je navržen pomocí analytického výpočtu a je nalezena metoda regulace, která kompenzuje pokles výstupního napětí. Metoda regulace je navržena a použita při návrhu transformátoru. Model je kontrolován pomocí simulace FEM.

Klíčová slova: Transformátor, Konstrukce, Simulace, Jednofázový transformátor, Regulace.

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LIST OF SYMBOLS AND ABBREVIATIONS USED

AC	Alternating Current
EMF	Electro Motive Force
RMS	Root Mean Square
FEM	Finite Element Method
f	Frequency
Hz	Hertz
A	Ampere
m	Meter
V	Volt
N	Number of turns
N_P	Number of primary turns
N_S	Number of secondary turns
B	Flux density
B_m	Maximum flux density
T	Tesla
Φ	Magnetic flux
Φ_{max}	Maximum magnetic flux
Wb	Weber
I	Current
I_p	Primary current
I_s	Secondary current
H	Magnetic field strength
R	Resistance
ρ	Resistivity
Ω	Ohm
T	Temperature
'C	Celsius
I_μ	Magnetizing Component
I_w	Working Component
U_p or V_p	Primary voltage
U_s or V_s	secondary voltage
VA	Volt Ampere
LV	Low voltage
HV	High voltage
K_W	Window space factor
Δ	Current density
Ac	Conductor area
d	Diameter
A_W	Window area
A_i	Net iron area
T_e	Turns per volts
K_s	Stacking factor
t	Time
s	seconds

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO TRANSFORMER

Transformer is a common device found in the electrical system which connects the circuits that are operating at different voltages. These are used in the applications where AC voltage conversion from one voltage level to another is needed. A Transformer is a static electrical device which transfers electrical energy from one coil to one or more coils without change within the frequency. A varying current in any one circuit of the transformer produces a fluctuating magnetic flux, which in turn induces a differing electromotive force across any other coils wound around the same core. Transformer is the important part for power supply system which are used in generation, transmission and distribution network. It is used to either to decrease or increase the voltage and currents by the use of transformer in AC circuits based on the requirements of the electrical equipment or device or load. Transformers are used in signals transmission with impedance matching for maximum power transfer. Transformers are also used in power electronics for energy conversion and control.

In power generation and transmission, the generator operate in the 10 to 20 kV range, whereas high voltage transmission is normally above 200 kV. In distribution, it will be 10 kV being further stepped down to 110Vor 230V for residential supplies. Transformers are also ideally suited to impedance matching for transfer maximum power, for example in an audio system where the speaker load resistance might be 8Ω. This would be matched to the output impedance of an amplifier measured in kΩ. An important application for power electronics is electrically isolating one circuit from another to satisfy safety regulatory requirements.

A fundamental principle of transformer operation is that the size is inversely proportional to the operating frequency, and this has opened up the role of the transformer from its more traditional role at power frequencies. When the transformer is used in power electronics applications that incorporate electrical isolation, the voltage that appears across a switch can be adjusted by the transformer to reduce the stresses on the switch.

A transformer consists of two or more mutually coupled windings. An alternating voltage source is connected to one of the windings usually referred to as the primary winding and this produces a changing magnetic flux field in accordance with the Faraday's laws. The resultant flux will depend on the number of turns in the primary winding. Normally the windings are wound on a core of magnetic material without an air gap to obtain high flux levels, so therefore the flux will depend on the reluctance of the core, including the physical dimensions of the core length and cross-sectional area in addition to the number of turns.

The manufacturing process may produce a very small air gap, which has the advantage of being able to control the magnitude of the inrush current. The magnetic flux is coupled to the other winding called the secondary winding and a voltage is induced in accordance with laws of electromagnetic induction. An inductor stores energy whereas in a transformer, the energy is transferred from the primary to the secondary load. Normally, iron laminations are used in the construction of large mains transformers to reduce eddy current loss in the core. Compressed ferromagnetic alloys are used in power electronic circuit applications for high frequency operation.

1.2 OBJECTIVES

To explain theoretical background of the transformer and to design a single phase transformer with high current output according to requirements of laboratory measurement of electrical apparatus.

To check the analytic design of transformer using FEM simulator and to find a solution for voltage drop because of temperature rise with help of analytical calculations in laboratory situations. To apply the selected compensation method into design of transformer.

1.3 CHAPTER ORGANISATION

The rest of report is organized as follows.

Chapter 2 - provides the working principle, construction and types of transformer.

Chapter 3 - provides theoretical background of transformer.

Chapter 4 - provides analytical design calculation of the transformer.

Chapter 5 - provides the details about FEM design of the transformer.

Chapter 6 - provides regulation method for voltage drop.

Chapter 7 - provides a brief conclusion.

CHAPTER 2

TRANSFORMER BASICS

2.1 WORKING PRINCIPLE

The basic working principle of a transformer is the phenomenon of mutual induction between two windings linked by common magnetic flux. The figure 2.1 shows the basic form of a transformer.

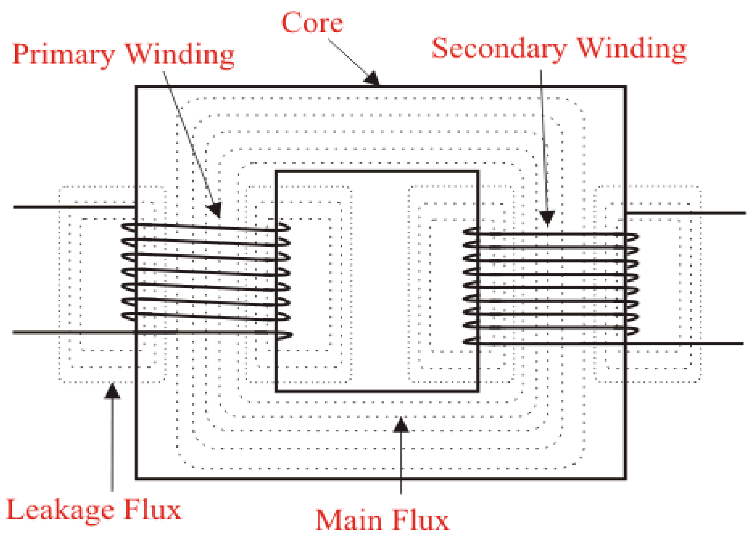

Figure 2.1 Basic Form of a Transformer

A transformer consists of two inductive coils which are primary winding and secondary winding. The coils are magnetically linked to each other but electrically separated. When a source of alternating voltage is connected to primary winding, alternating magnetic flux is produced around the winding. A magnetic path is provided by the core for the flux to get linked with the secondary winding. The flux which gets linked with the secondary winding are called as main flux and the flux which does not get linked with secondary winding are called as leakage flux. Alternating electro-motive force are produced by the flux as the direction of it is continuously changing gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This electro-motive force is called mutually induced emf, and the frequency of mutually induced emf is same as that of supplied emf. If the secondary winding is closed circuit, then mutually induced current flows through closed circuit, and the electrical energy is transferred magnetically from one coil to another coil. The Faraday's law of electromagnetic induction can be expressed as,

$$e = M \times dI/dt \text{ ....(2.1)}$$

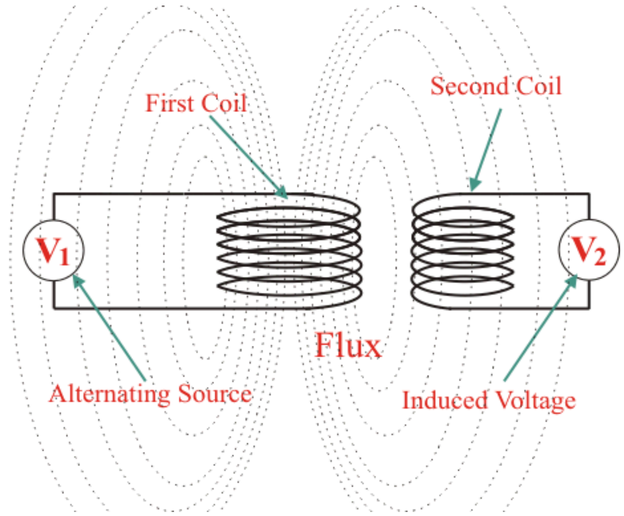

Figure 2.2 Magnetic Flux on transformer

The alternating voltage source is given to the first coil and hence it can be called as the primary winding. The energy which is induced drawn out from the second coil and thus can be called as the secondary winding. Thus electrical energy transferred magnetically from primary winding to secondary winding.

2.2 CONSTRUCTION

The basic construction of transformer consist of two windings coupled through a magnetic medium wounded in limbs of iron. These two windings works at different voltage level which are called high voltage winding and low voltage winding. Both winding are wounded on common core consist of steel laminations. One of the winding is connected to ac power supply which is called primary winding and other winding is connected to load which is called secondary winding.

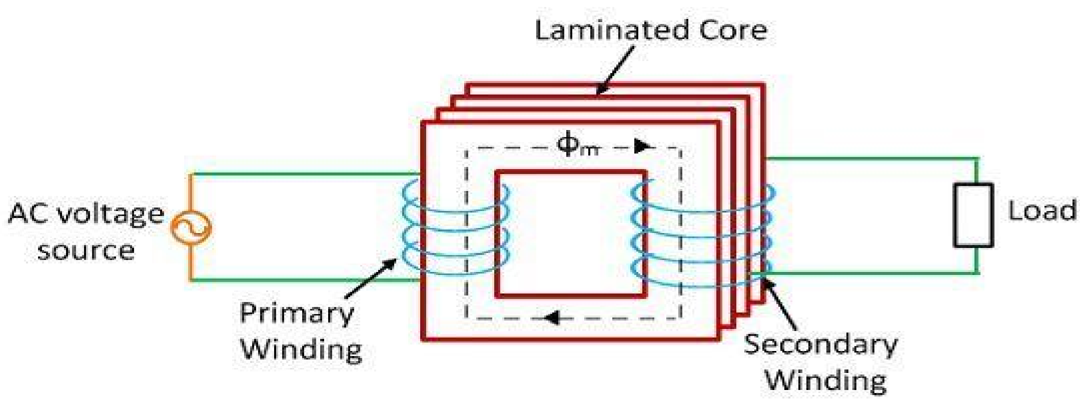

Figure 2.3 Basic structure of a Transformer

The construction of transformers varies greatly depending on their applications, design, winding voltage, current ratings and operating frequencies.

2.3 TYPES BASED ON THEIR CORE CONSTRUCTION

The transformer are classified into two based on their core design which are,

- Core type transformer
- Shell type transformer

2.3.1 Core Type Transformer

In core type transformer, the magnetic core is constructed with laminations in order to form a rectangular frame and the windings are arranged concentrically with respect to other around the legs or limbs. The top and bottom horizontal portion of the core are called yoke. The yokes connect the two legs and have a cross sectional area equal to or greater than that of legs. Each leg carries one half of primary and secondary winding. The two windings are closely coupled together in order to reduce the leakage reactance. The low voltage winding is wound near the core and high voltage winding is wound over low voltage winding away from core in order to reduce the amount of insulating materials.

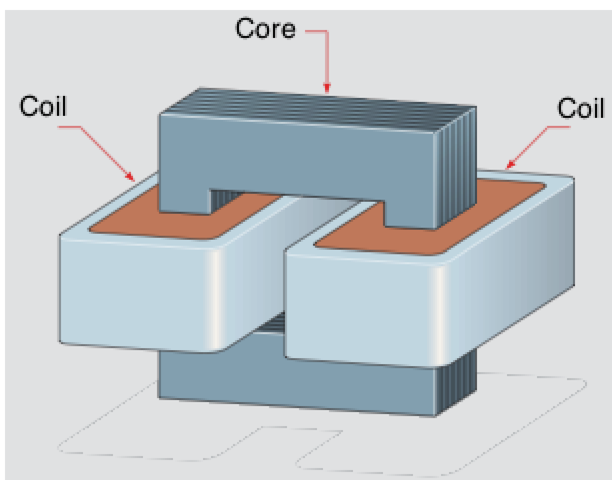

Figure 2.4 Core Type Transformer

In core type transformer, the coils are wounded in helical layers with different layers insulated from one another by materials like mica. The core is having two rectangular legs and the coils are placed on both the legs in the core type. The coils used are of form-wound and cylindrical type on the core type. It has a single magnetic circuit.

3.2.2 Shell Type Transformer

Shell type transformers are the most popular and efficient transformers. The Shell type transformer has a double magnetic circuit. The core has three legs and both the winding are placed on the central legs. The core encircles most parts of the winding. Generally multi-layer disc and sandwich coils are equipped in shell type.

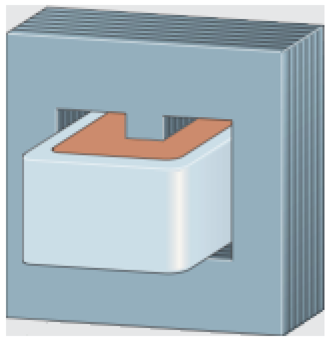

Figure 2.5 Shell type transformer

Each high voltage coil is in between two low voltage coils and low voltage coils are nearest to top and bottom of the yokes. The shell type construction is mostly suitable for operating at very high voltage of transformer. In the shell type transformer, the winding in the shell type is surrounded by the core itself as natural cooling does not exist. The winding of transformer are needed to be removed for better maintenance which can easily damaged.

In shell type transformers the windings are put around the central leg and the flux path is completed through two side legs. The central leg or limb carries total mutual flux while the side limbs forming a part of a parallel magnetic circuit carry half the total flux. The cross sectional area of the central limb is twice that of each side limbs. Leakage flux can be reduced in shell type transformer.

2.4 TYPES BASED ON THEIR PHASES

The transformer are classified into two based on their phase which are,

- Single phase transformer
- Three phase transformer

2.4.1 Single phase transformer

A single phase transformer is a type of power transformer that utilizes single phase alternating current, that mean the transformer relies on a voltage cycle that operates in a unified time phase.

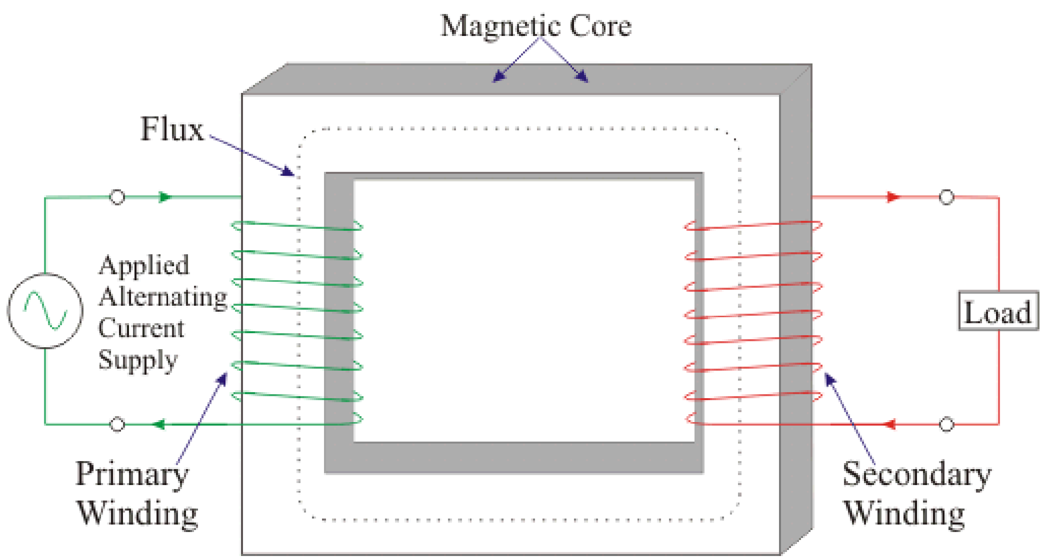

Figure 2.6 Single phase transformer

It contains two coils of electrical wire for inner and outer windings. The primary is usually known to have the high amount of voltage. Both coils are wrapped around a common closed magnetic iron circuit which is referred to as the core. The core is made up of several layers of iron, laminated together to decrease losses. The common core allows power to be transferred from one coil to the other without an electrical connection as they are linked on it. When current flows through the primary coil, a magnetic field is created that induces a voltage in the secondary coil. Usually, the primary coil which has the high voltage comes in and then is transformed to create a magnetic field. The secondary coil job is to transform the alternating magnetic field into electric power, supplying the required voltage output.

2.4.2 Three phase transformer

Three phase transformers are used to step-up or step-down the high voltages in various stages of power transmission system. The power generated at various generating stations is in three phase nature and the voltages are in the range of 13.2KV or 22KV. In order to reduce the power loss to the distribution end, the power is transmitted at somewhat higher voltages like 132 or 400KV. Hence, for transmission of the power at higher voltages, three phase step-up transformer is used to increase the voltage. Also at the end of the transmission or distribution, these high voltages are step-down to levels of 600, 400, 230 volts, etc. For this, a three phase step down transformer is used.

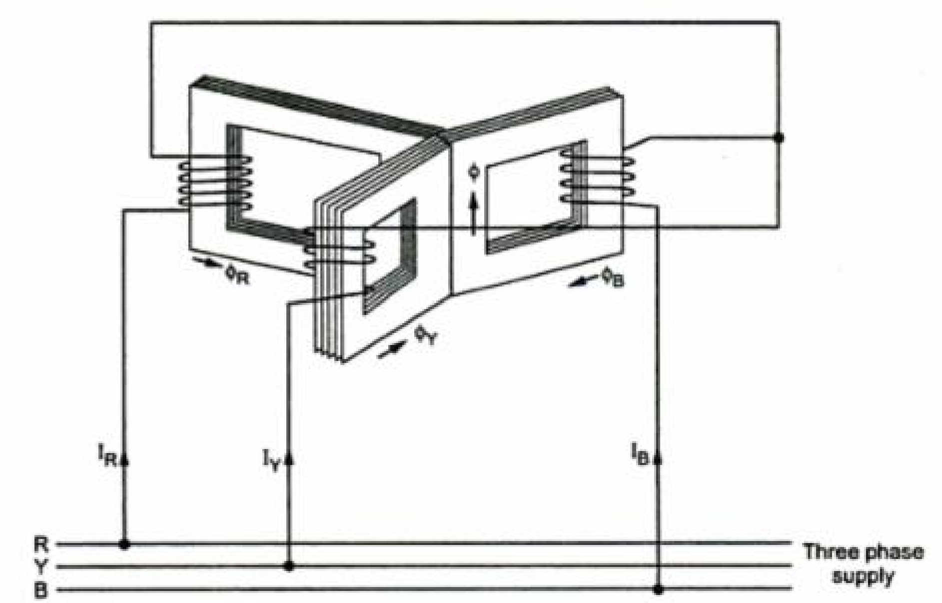

Figure 2.7 Three phase transformer connection

2.5 TYPES BASED ON THEIR FUNCTIONS

The transformer are classified into two based on their functions which are,

- Step-up transformer
- Step-down transformer

2.5.1 Step-up Transformer

A transformer in which the output voltage is higher than its input voltage is called a step-up transformer. The step-up transformer decreases the output current for keeping the input and output power of the system equal.

Considered a step-up transformer shown in the figure below. The E_1 and E_2 are the voltages, and T_1 and T_2 are the number of turns on the primary and secondary winding of the transformer.

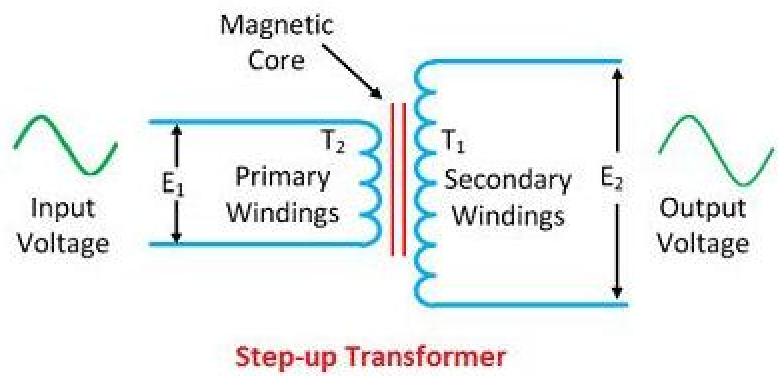

Figure 2.8 Step-up transformer

The number of turns on the secondary of the transformer is greater than that of the primary, that is $T_2 > T_1$. Thus the voltage turn ratio of the step-up transformer is 1:2. Step-up transformer are mainly used in generation side of the power system where the power generated in power station transferred through transmission lines needs high voltages for transfer.

2.5.2 Step-down Transformer

A transformer in which the output voltage is lesser than its input voltage is called a step-down transformer. The number of turns on the primary of the transformer is greater than the turn on the secondary of the transformer, That is $T_2 < T_1$.

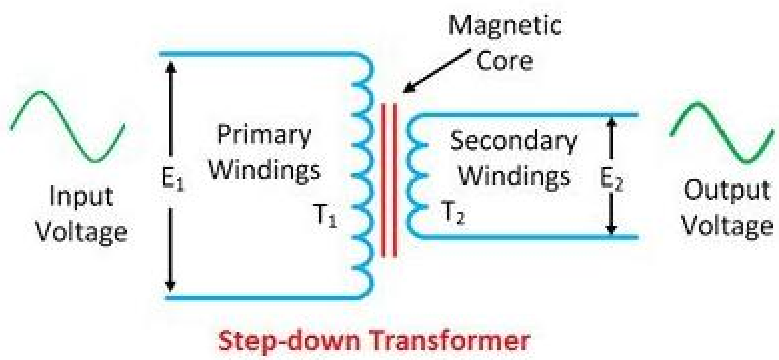

Figure 2.9 Step-down transformer

The voltage turn ratio of the step-down transformer is 2:1. The voltage turn ratio determines the magnitude of voltage transforms from primary to secondary windings of the transformer. Step-down transformers are mainly used in distribution side of the power supply system where the high voltages converted into low voltage levels.

2.6 TYPES BASED ON THEIR COOLING METHOD

2.6.1 Air Natural Or Self Air Cooled Transformer

This type of cooling method of the transformer is generally used in small transformers up to 3 MVA. In this method the transformer is allowed to cool by the surrounding natural air flow through heat radiation.

2.6.2 Air Blast Type

For transformers rated more than 3 MVA, natural air cooling method is inadequate. In this method, fans or blowers are used to force the air on the core and windings. The air supply must be filtered to prevent the accumulation of dust particles in ventilation ducts. This method can be used for transformers up to 15 MVA. The transformer is housed in a thin sheet metal box open at both ends through which air is blown from the bottom to the top.

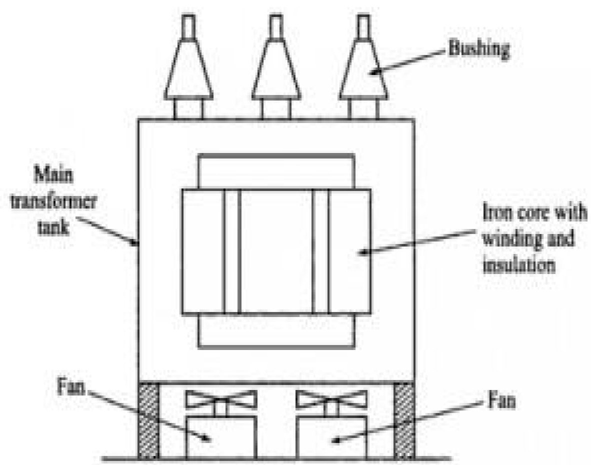

Figure 2.10 Air blast type

2.6.3 Oil Filled Self-Cooled Type

Oil filled self-cooled type uses small and medium-sized distribution transformers. The assembled windings and core of such transformers are mounted in a welded, oil-tight steel tanks provided with a steel cover. The tank is filled with purified, high quality insulating oil as soon as the core is put back at its proper place. The oil helps in transferring the heat from the core and the windings to the case from where it is radiated out to the surroundings.

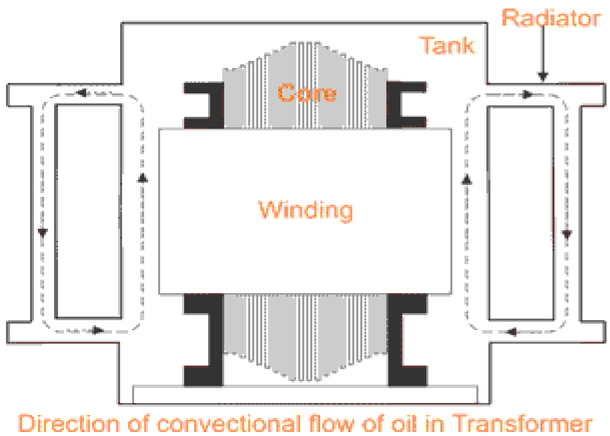

Figure 2.11 Oil filled self cooling type

For smaller sized transformers the tanks are usually smooth surfaced, but for large size transformers a greater heat radiation area is needed, and that too without disturbing the cubical capacity of the tank. This is achieved by frequently corrugating the cases. Still larger sizes are provided with radiation or pipes.

2.6.4 Oil Filled Forced Air Cooled Type

In this type the transformer is cooled by the oil which in turn cooled by the forced air in radiator. A bank of coolers or blowers is situated in the transformer radiator which forces the air through the cooling fins. The hot oil enters in these cooling fins by the natural convention and cooled oil again flows through the windings. This cooling method is used normally large transmission transformers situated outdoors, in power plants and in power stations

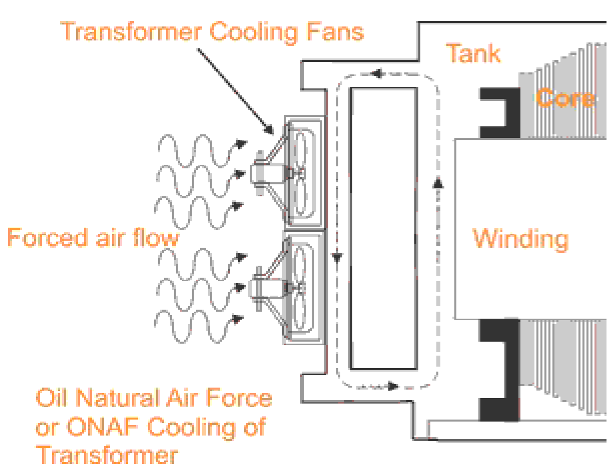

Figure 2.12 Oil Filled Forced Air Cooled Type

2.6.5 Oil Filled Water Cooled Type

This type is used for much more economic construction of large transformers, as the above-told self-cooled method is very expensive. The same method is used here as well- the windings and the core are immersed in the oil. The only difference is that a cooling coil is mounted near the surface of the oil, through which cold water keeps circulating.

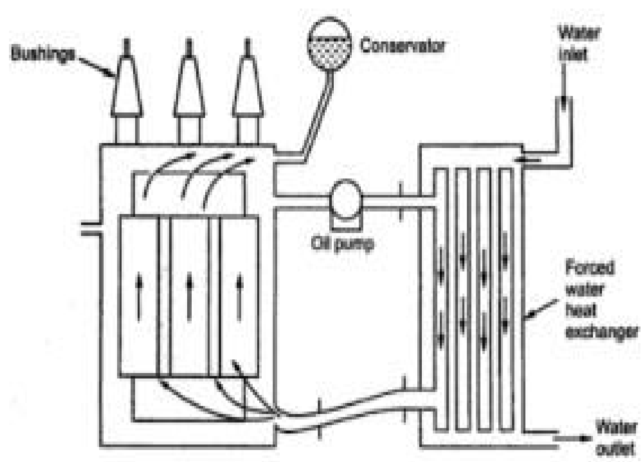

Figure 2.13 Oil filled water cooled type

This water carries the heat from the device. This design is usually implemented on transformers that are used in high voltage transmission lines. The biggest advantage of such a design is that such transformers do not require housing other than their own. This reduces the costs by a huge amount. Another advantage is that the maintenance and inspection of this type is only needed once or twice in a year.

2.7 TYPES BASED ON THEIR USE

2.7.1 Power Transformer

The Power transformer is a one kind of transformer, that is used to transfer electrical energy in any part of the electrical or electronic circuit between the generator and the distribution primary circuits. These transformers are used in distribution systems to interface step up and step down voltages. The common type of power transformer is liquid immersed and the life span of these transformers is around 30 years.

Power transformers can be classified into three types based on the ranges. They are small power transformers, medium power transformers and large power transformers. These transformers transform the voltage. It holds a low voltage, high current circuit at one side of the transformer and on the other side of the transformer it holds high voltage low current circuit.

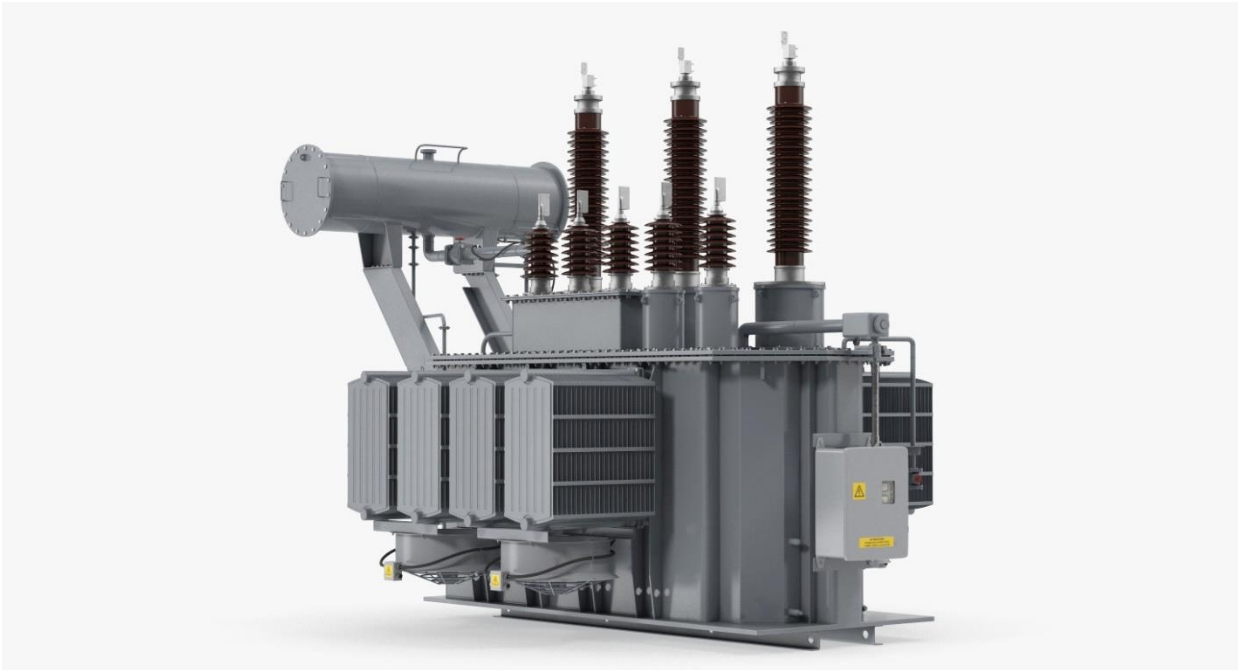

Figure 2.14 Power transformer

Power transformer depends on the principle of Faradays induction. They describe the power system into zones where every gear connected to the system is sized per the ratings set by the power transformer.

2.7.2 Distribution Transformer

Distribution transformer is an electrical isolation transformer which converts high voltage electricity to lower voltage levels acceptable for uses in homes and business. A distribution transformer's function is to step down the voltage and provide isolation between primary and secondary.

Figure 2.15 Distribution transformer

Electrical energy is passed through distribution transformers to reduce high distribution voltage levels down to end user level. Nearly all the energy passes through at least one distribution transformer before being consumed by an end user appliance, or motor etc. Distribution transformers are found in all sectors of economy, that are residential, commercial and industrial.

2.7.3 Instrument transformer

Instrument transformers are high accuracy class electrical devices used to isolate or transform voltage or current levels. The most common usage of instrument transformers is to operate instruments or metering from high voltage or high current circuits, safely isolating secondary control circuitry from the high voltages or currents. The primary winding of the transformer is connected to the high voltage or high current circuit, and the meter or relay is connected to the secondary circuit.

Figure 2.16 Instrument transformer

Instrument transformers may also be used as an isolation transformer so that secondary quantities may be used in phase shifting without affecting other primary connected devices. Instrument transformer are also used with protective relays for protection of power system. Instrument transformer are of two types

- Current transformer
- Potential transformer

Current Transformer

This type of transformer can be used in power systems to step down the voltage from a high level to a low level with the help of a 5A ammeter. This transformer includes two windings like primary and secondary. The current in the secondary winding is proportional to the current in the primary winding as it generates current in the secondary winding. The circuit diagram of a typical current transformer is demonstrated in the following figure.

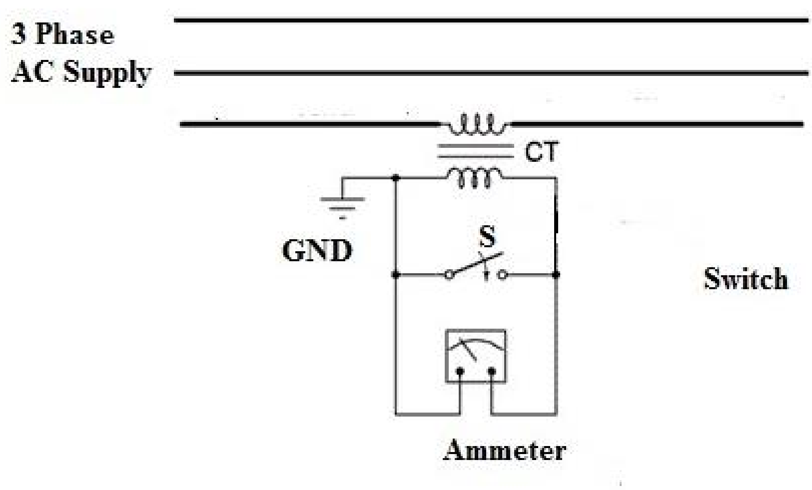

Figure 2.17 Current transformer

In this transformer, the primary winding consists of few turns and it is connected with the power circuit in series. So it is called a series transformer. Likewise, the secondary winding includes a number of turns and it is connected to an ammeter directly because the ammeter includes small resistance. Thus, the secondary winding of this transformer works almost in the condition of a short circuit. This winding includes two terminals where one of its terminals is connected to ground to evade the huge current. So insulation breakdown chances will be reduced to guard the operator from huge voltage.

The secondary winding of this transformer in the above circuit is short-circuited before disconnecting the ammeter with the help of a switch to avoid the high voltage across the winding.

Potential Transformer

This type of transformer can be used in power systems to step down the voltage from a high level to a lower level with the help of a small rating voltmeter which ranges from 110 Volts to 120 Volts. A potential transformer typical circuit diagram is illustrated below.

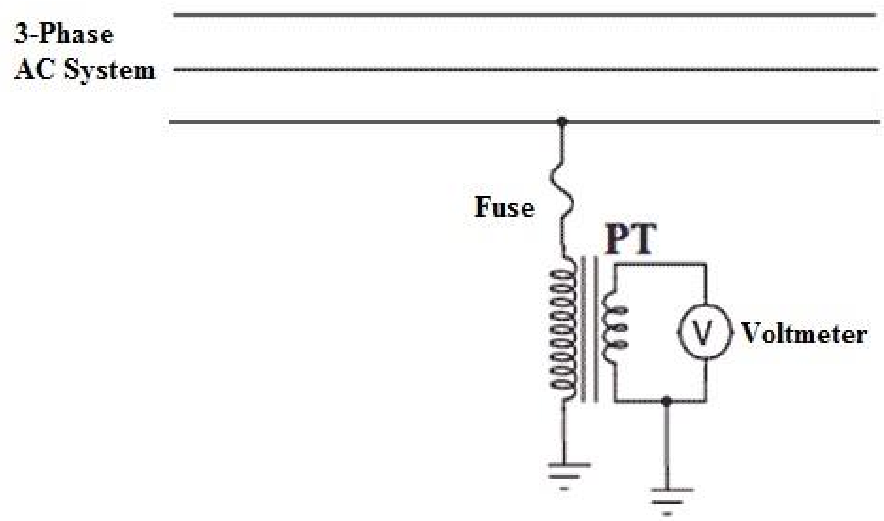

Figure 2.18 Potential transformer

This transformer includes two windings like a normal transformer like primary & secondary. The primary winding of the transformer includes a number of turns and it is connected in parallel with the circuit. So it is called a parallel transformer. Similar to the primary winding, the secondary winding includes fewer turns and that is connected to a voltmeter directly because it includes huge resistance. Therefore the secondary winding works approximately in open circuit condition. One terminal of this winding is connected to the earth to maintain the voltage with respect to the earth to protect the operator from a huge voltage.

CHAPTER 3

THEORETICAL BACKGROUND OF TRANSFORMER

3.1 EMF EQUATION OF TRANSFORMER

The number of turns of the coil of either of the primary or secondary coil determines the amount of current it induces or is induced by it. When the current applied to the primary is reduced, the strength of the magnetic field is reduced and the same for the current induced in the secondary winding.

$$E = N\,(d\Phi/dt)\text{............................}(\ 3.1)$$

The Amount of voltage induced in the secondary winding is given by the equation:

Where N is the number of turns in the secondary winding.

As the flux varies sinusoidal, the magnetic flux

$$\Phi = \Phi_{max}\,\sin\omega t\text{..............................}(\ 3.2)$$

thus,

$$E = N\times w\times\Phi_{max}\times\cos(\omega t)\ \text{...............}(\ 3.3)$$

$$Emax = Nw\times\Phi_{max}\text{............................}(\ 3.4)$$

The root mean square value of the Induced Emf is gotten by dividing the maximum value of the emf by √2

Thus we have

$$Erms = \Phi_{max}\times Nw/\sqrt{2}\text{............................}(\ 3.5)$$

$$\text{or } Erms = f\times N\ \times\Phi_{max}\times 2\pi/\sqrt{2}\text{................}(\ 3.6)$$

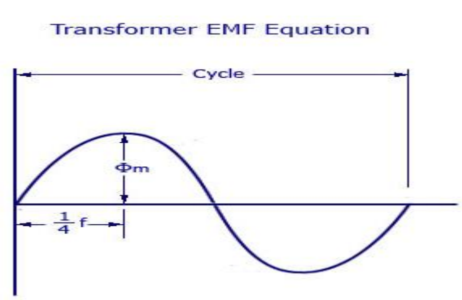

Figure 3.1 Sin wave

Thus,

$$Erms = 4.44fN\Phi_{max} \qquad (3.7)$$

This equation is known as the transformers EMF equation.

Where: N is the number of turns in coil winding

f is the flux frequency in hertz

Φ is the magnetic flux density in Weber

with all these values determined, the transformer can thus be constructed.

3.2 EFFICIENCY OF A TRANSFORMER

The efficiency of a transformer is determined by the equation,

$$\text{Efficiency} = (\text{ output power / input power }) \times 100\% \qquad (3.8)$$

While the power output of an Ideal transformer should be the same as the power input, most transformers are far from the Ideal transformer and do experience losses due to several factors.

Some of the losses that can be experienced by a transformer are listed below

- Copper Losses
- Hysteresis losses
- Eddy current losses

3.2.1 Copper Losses

These losses are sometimes referred to as winding losses or I^2R losses. These losses are associated with the power dissipated by the conductor used for the winding when current is passed through it due to the resistance of the conductor. The value of this loss can be calculated using the formula,

$$P = I^2R \qquad (3.9)$$

3.2.2 Hysteresis losses

This is a loss related to the reluctance of the materials used for the core of the transformer. As the Alternating current reverses its direction, it has an impact on the internal structure of the material used for the core as it tends to undergo physical changes which also uses up part of the energy

3.2.3 Eddy Current Losses

This is a loss typically conquered by the use of laminated thin sheets of steel. The eddy current loss arises from the fact that the core is also a conductor and will induce an emf in the secondary coil. The currents induced in the core according to faradays law will oppose the magnetic field and lead to the dissipation of energy.

Factoring the effect of these losses into the transformer's efficiency calculations, we have,

Efficiency = (output power - losses / input power) ×100%...........................(3.10)

3.3 EQUIVALENT CIRCUIT DIAGRAM

Equivalent circuit diagram of a transformer is basically a diagram which can be resolved into an equivalent circuit in which the resistance and leakage reactance of the transformer are imagined to be external to the winding.

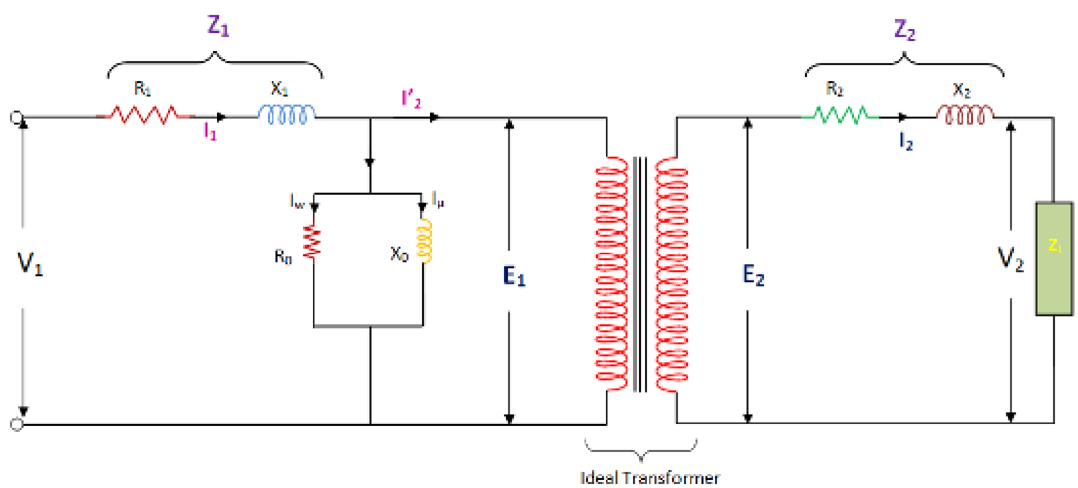

Figure 3.2 The Equivalent circuit diagram of transformer

Where,
R_1 = Primary Winding Resistance.
R_2= Secondary winding Resistance.
I_0= No-load current.
I_μ = Magnetizing Component,
I_w = Working Component,

This I_μ & I_w are connected in parallel across the primary circuit. The value of E_1 that is Primary e.m.f is obtained by subtracting vector $I_1 Z_1$ from V_1 . The value of $X_0 = E_1 / I_0$ and $R_0 = E_1 / I_w$. We know that the relation of E_1 and E_2 is $E_2 / E_1 = N_2 / N_1 = K$, that is transformation Ratio

From the equivalent circuit , it can be easily calculate the total impedance of to transfer voltage, current, and impedance either to the primary or the secondary. The secondary circuit and its equivalent primary value is shown in figure below,

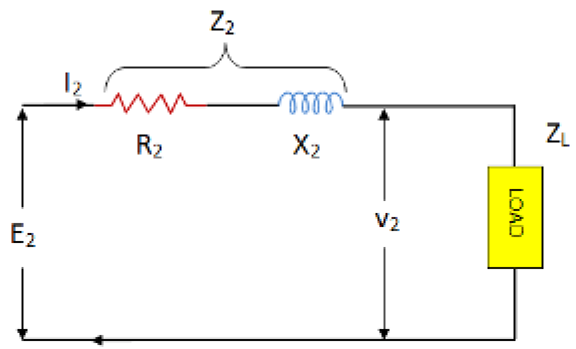

Figure 3.3 The secondary circuit

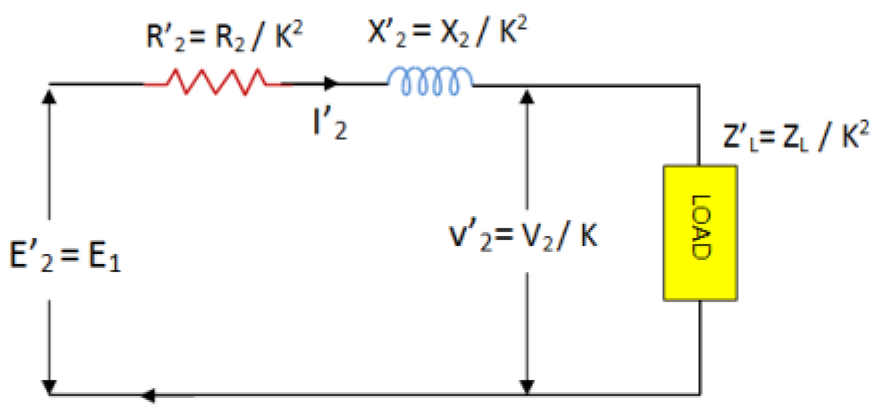

Figure 3.4 Equivalent primary value

The total equivalent circuit of the transformer is obtained by adding in the primary impedance as shown in figure below.

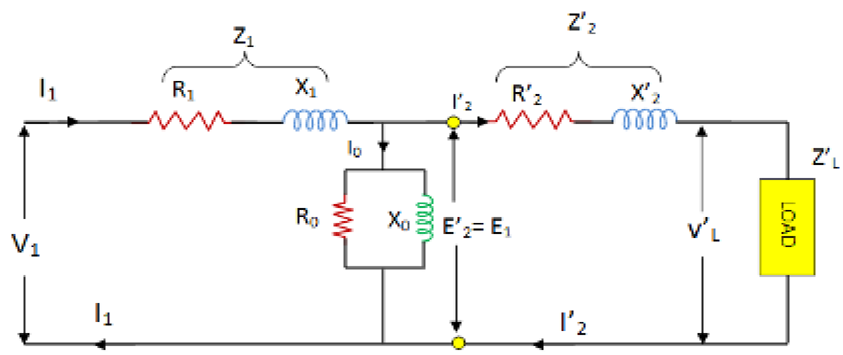

Figure 3.5

And It can be simplified the terminals shown in figure 3.6 & further simplify the equivalent circuit is shown in figure 3.7 ,

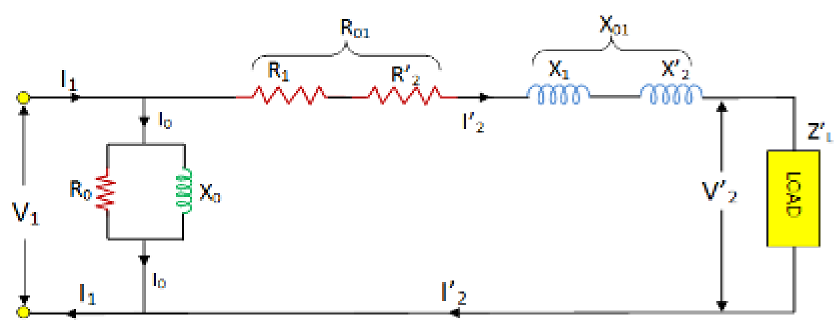

Figure 3.6

At last, the circuit is simplified by omitting I_0 altogether as shown in figure 3.7 .

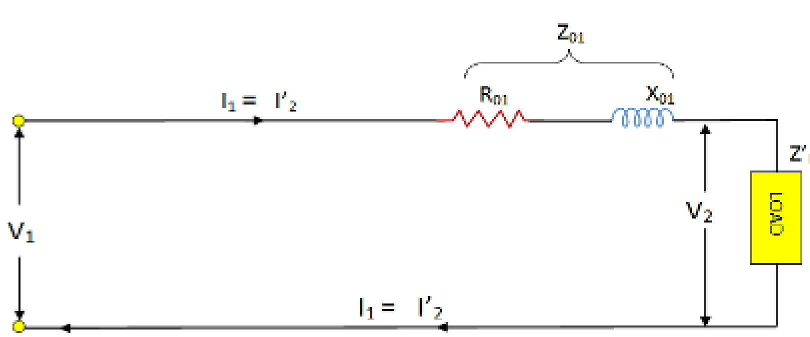

Figure 3.7

From the equivalent circuit which is shown in figure 3.5 , the total impedance between the input terminal is ,

$$Z = Z_1 + Z_m \,//\, (Z_2' + Z_L') = (Z_1 + (Z_m (Z'_m + Z'_L))\div (Z_m + (Z'_2 + Z'_L))) \quad \text{.........................(3.11)}$$

This is so because there are two parallel circuits, one having an impedance of Z_m and the other having Z'_2 and Z'_L in series with each other.

$$V_1 = I_1 [Z_1 + (Z_m (Z'_m + Z'_L))\div (Z_m + (Z'_2 + Z'_L))] \quad \text{...........................(3.12)}$$

3.4 OUTPUT EQUATION OF SINGLE PHASE TRANSFORMER

The equation which relates the rated kVA output of a transformer to the area of core and window is called output equation. In transformers the output kVA depends on flux density and ampere-turns. The flux density is related to core area and the ampere-turns is related to window area. The simplified cross-section of core type and shell type single phase transformers are shown in figures. The low voltage winding is placed nearer to the core in order to reduce the insulation requirement. The space inside the core is called window and it is the space available for accommodating the primary and secondary winding. The window area is shared between the winding and their insulations.

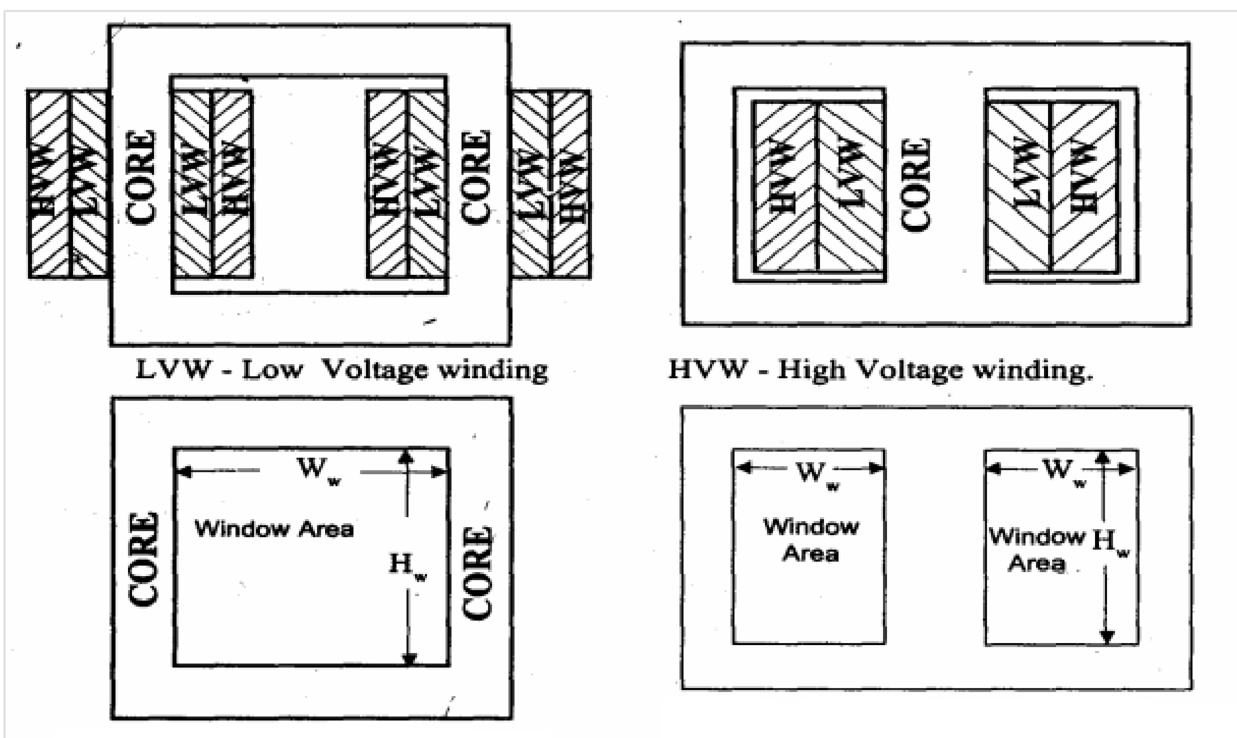

Figure 3.8 Cross section of core and shell type of single phase transformer

The induced emf in a transformer,

$$E = 4.44fN\Phi_{max}\text{............................}(3.13)$$

Emf per turn,

$$E_T = E / N = 4.44f\Phi_{max}\text{............................}(3.14)$$

The window in single phase transformer contains one primary and one secondary winding .The window space factor K_w is the ratio of conductor area in window to total area of window.

Window space factor K_W = (conductor area in window / area of window) = A_C / A_W........(3.15)

Conductor area in window,

$$A_C = K_W A_W\text{............................}(3.16)$$

The current density is same in both the windings. Therefore Current density,

$$\delta = \frac{Ip}{Ap} = \frac{Is}{As}\text{ ....}(3.17)$$

Area of cross - section of primary conductor,

$$Ap = \frac{Ip}{\delta}\text{ ....}(3.18)$$

Area section of secondary conductor,

$$As = \frac{Is}{\delta}\text{ ....}(3.19)$$

If we neglect magnetizing mmf then primary ampere turns is equal to secondary ampere turns. Therefore ampere turns,

$$AT = I_P T_P = I_S T_S\text{............................}(3.20)$$

Total copper area in window,

Ac = Copper area of primary winding + Copper area of secondary winding = (Number of primary turns x area of cross-section of primary conductor) + (Number of secondary turns x area of cross - section of secondary conductor)

$$A_C = I_P A_P + I_S A_S = (I_P T_P + I_S T_S) / \delta = 2AT/ \delta\text{............................}(3.21)$$

On equating the above equations, we get,

$$K_W A_W = 2AT / \delta\text{............................}(3.22)$$

Therefore Ampere turns,

$$AT = K_W \, A_W \, \delta \, / \, 2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.23)$$

The kVA rating of single phase transformer is given by,

$$\text{kVA rating } Q = V_P \, I_P \times 10^{-3} \approx E_P \, I_P \times 10^{-3} \quad (E_P \approx V_P) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.24)$$

Multiplying and dividing bt T_P

$$Q = (E_P / T_P) \times \; T_P \, I_P \times 10^{-3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.25)$$

$$Q = E_T \, AT \times 10^{-3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.26)$$

On substituting for E and AT from equations we get,

$$Q = \; (4.44 f \Phi_{max} \, K_W \, A_W \, \delta \, / \, 2 \,) \times 10^{-3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.27)$$

$$Q = 2.22 \; f \, \Phi_{max} \, K_W \, A_W \, \delta \times 10^{-3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.28)$$

$$Q = 2.22 \; f \, B_m \, A_i \, K_W \, A_W \, \delta \times 10^{-3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.29)$$

The above equation is the output equation of single phase transformer.

CHAPTER 4

ANALYTICAL CALCULATION OF THE TRANSFORMER

4.1 DESIGN CALCULATION

In this section, design for the construction of single phase core type transformer has been presented. The design of core and the windings has been discussed. Design includes the area of cross section and number of turns of primary and secondary side.

Specifications

The designed transformer is of 1 KVA, 230 V/ 2 Volts, 50 Hz, Single phase, Core type transformer. Design and fabrication of this transformer has been made possible by the special calculations and design procedure.

Core Design

The design of the core is presented by the following procedure. Design constants in this design procedure are certain as for the small transformers.

Ai= Net Iron Area of Core

$Ai = C\times10^{-4}\times \sqrt{\frac{U.I}{k.f}}$

Lets Flux density = Bm = 1.2 web/m2 , f =Supply frequency = 50 Hz, C = 7 for air ventilation, k = 2 for single phase.

$Ai = 0.0022\ m^2$

Ai = a × b

a = 50 mm

b = Ai / a = 44 mm

Turns per volt (Te) for a transformer is given as:

Te= 1/4.44×f× Bm×Ai

Te = 1.71 Turns/ V,

Number of turns:

No. of primary turns =N1 = U1 ×Te = 380 turns

No. of secondary turns =N2 = 1.04 ×U2 ×Te = 4 turns

Lets current density of copper δ = 2.3 mm^2

Area of primary winding Ap = $\frac{Ip}{\delta}$ =2 mm^2

Diameter d = $\sqrt{\frac{4.Ap}{\pi}}$ = 1.6 mm

Area of secondary winding As = $\frac{Is}{\delta}$ =217 mm^2

Diameter d = $\sqrt{\frac{4.As}{\pi}}$ = 16.62 mm

Resistance R = ρ×L/S = 1.2 mΩ

Primary resistance $R_p = N_p$ R = 0.456 Ω

Let Stacking factor Ks = 0.9

Window factor Kw = $\frac{8}{30+Kv}$ = 0.26

Gross core area Agi = Ai / Ks = 0.0024 m^2

Window area Aw = $\frac{1}{2.22\times f\times Bm\times Ai\times Kw\times\delta}$ = 5.71 mm^2

Conductor area Ac = Aw × Kw = 1.48 mm^2

Net area of yoke Ay = 1.2 × Ai = 0.00264 m^2

Width of yoke Dy = a = 50 mm

Height of yoke Hy = Ay / Dy = 52.8 mm

Tongue width = $\sqrt{Agi}$ = 0.049 m

Aw = Hw × Ww

Let $Hw / Ww = 3$ so $Hw = 3Ww$

$Aw = 3Ww^2$

Window width $Ww = \sqrt{\frac{Aw}{3}} = 1.38$ mm

Window height $Hw = 3Ww = 4.14$ mm

CHAPTER 5

FEM DESIGN OF THE TRANSFORMER

5.1 CORE DESIGN OF THE TRANSFORMER

The transformer is designed with help of ANSYS Maxwell simulation software. Ansys Maxwell is one of the industry leading electromagnetic field simulation software for design and analysis of electric motors, actuators, sensors, transformers and other electromagnetic and electromechanical devices. The nonlinear and transient motion of electromechanical components and their effects on the drive circuit and control system design are precisely characterized with the help of Maxwell software. The analytical method can only compute the axial components of the magnetic field in working of the transformer, the effects which produced by the radical components cannot be computed by the analytical method. The role of FEM model is to provide more accurate magnetic field calculation of transformer.

First step in the design is construction of core of the transformer, as magnetic core is main part of the transformer which magnetically transfers the electrical energy from primary coil to secondary coil. Core type transformer is selected for model to design according to analytical design calculation for construction.

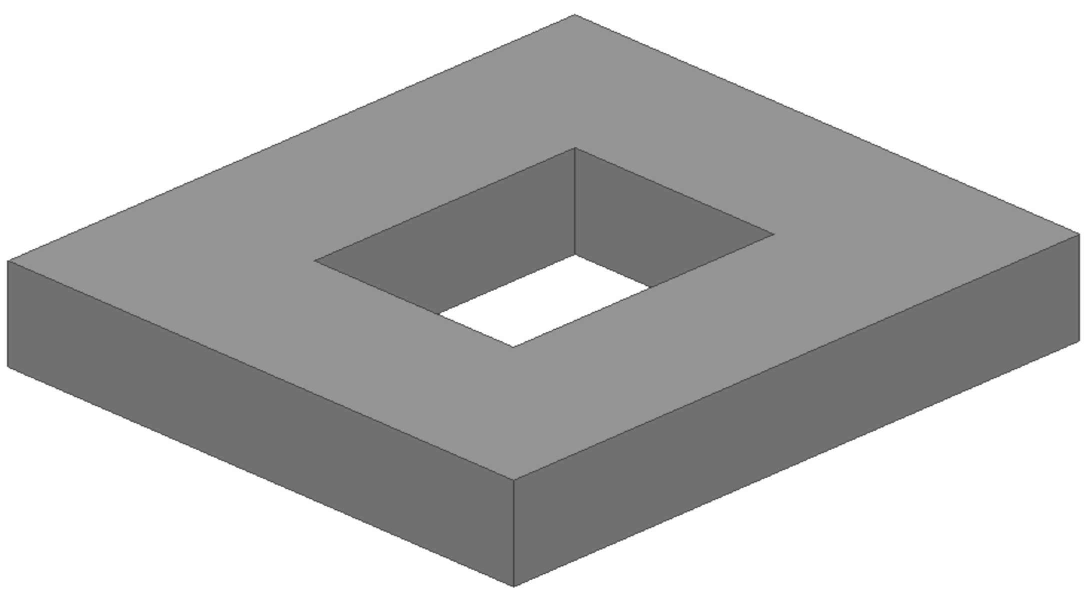

Figure 5.1 Magnetic Core of the Transformer

The above figure shows the core design in the 3D model of the transformer which is rectangular shape and core type transformer. The material of the core in design is steel for smooth operation for energy transfer which has good B-H curve. It provides high saturation flux density. Core area and window area are designed as per the analytical design calculations. Magnetic core is characterized with B-H curve with magnetization and thin laminations. The figure 5.2 shows relation between the magnetic field strength with flux density of the material which selected for core design.

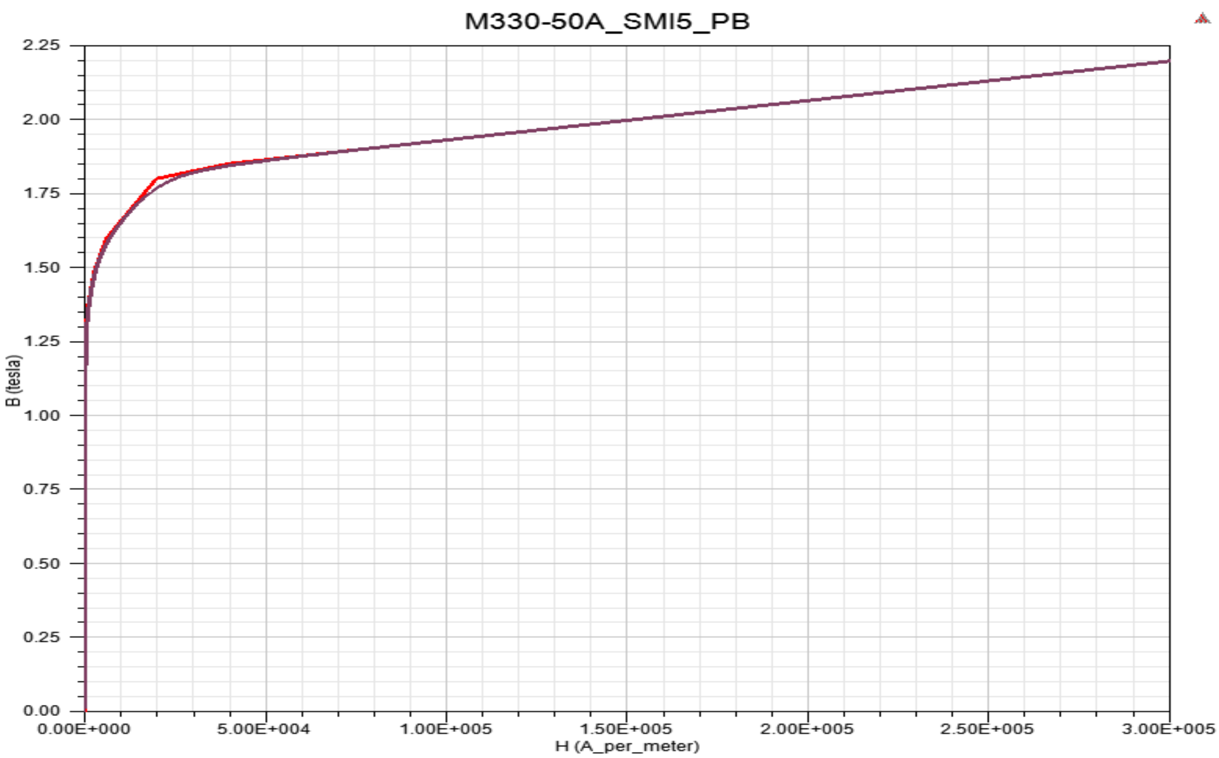

Figure 5.2 B-H Curve of Core Material

5.2 DESIGN OF THE WINDINGS

Next step in the design is the construction of primary winding and secondary winding of the transformer. As number of turns of primary winding is higher than secondary winding, the design of primary coil will looks different from secondary coil. The figure 5.3 shows the design of 3D model of the primary winding of transformer. The design looks like rectangular shape but the coils are wounded in that shape. The number of turns of primary winding is 380 turns so coils are wounded around the magnetic core such a fashion look like solid but it separated inside that rectangular conductor. The primary winding is HV side of the Transformer which has constant power AC supply of 230V 50Hz.

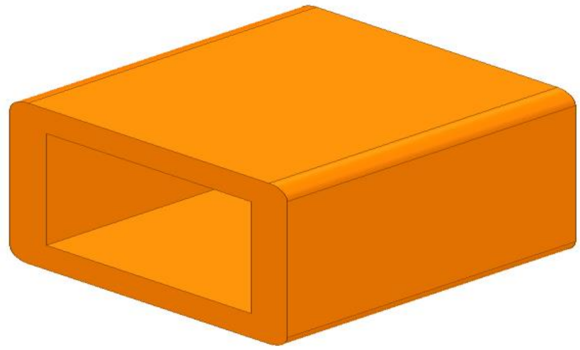

Figure 5.3 Primary Coil of the Transformer

The secondary winding of the transformer designed differently compare to primary winding which has higher turns. The figure 5.4 shows the design of 3D FEM model of the secondary winding of transformer. The number of turns of secondary winding is 3.6 turns because the voltage of secondary winding is low. The secondary voltage induced will be 2 V. The secondary winding is LV side of the transformer. The secondary current is higher than primary current that is 10:1 ratio. The secondary coil will be bigger due to high current output so the coil width will be little bit higher than calculated value.

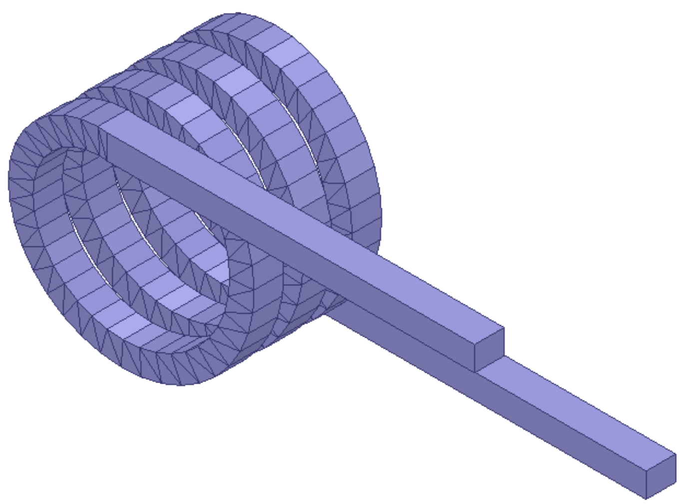

Figure 5.4 Secondary Coil of the Transformer

The material selected for both primary winding and secondary winding are copper for its good conductivity and common usage in the construction of transformer winding. Copper has the highest conductivity than any other non precious material. It has high ductility, good resistance for corrosion, medium strength and easy of joining so copper is used in cables. The figure 5.5 shows the final design of 3D FEM model of the transformer.

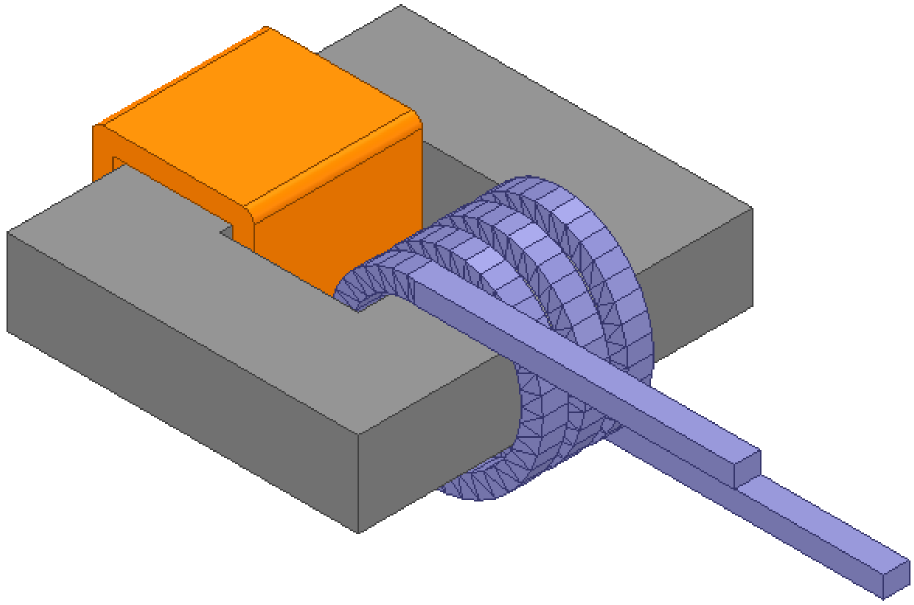

Figure 5.5 Final Design of the Transformer

5.3 RESULTS

After designing of the transformer, next step is to input the parameter to analysis the model works properly. The input of primary winding will be 230V 50Hz AC supply and when the supply flows through the primary winding, an alternating magnetic flux is produced around the winding.

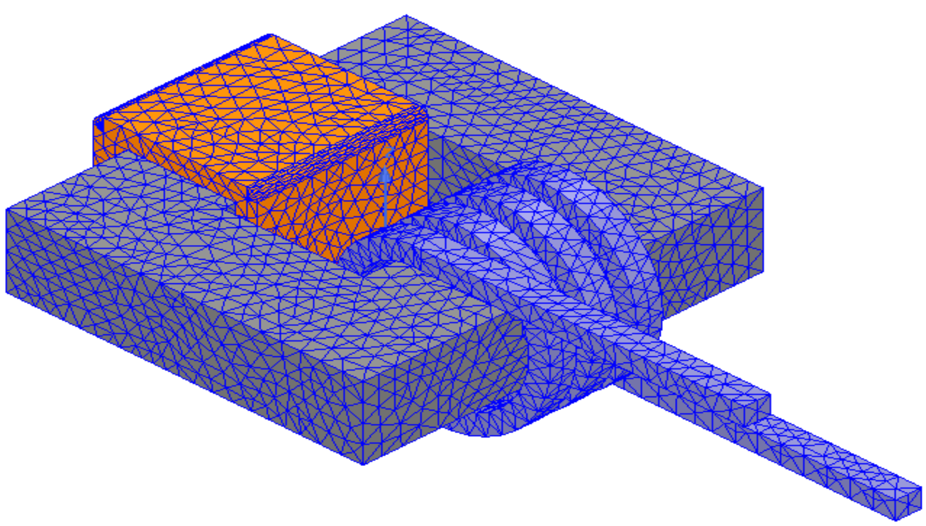

Figure 5.6 Mesh at transformer model

A magnetic path is provided by the core for the flux to get linked with the secondary winding and mutual emf induced in the secondary winding. The figure 5.6 shows the mesh operation of the designed transformer. The mesh was generated in the transformer as shown in the figure.

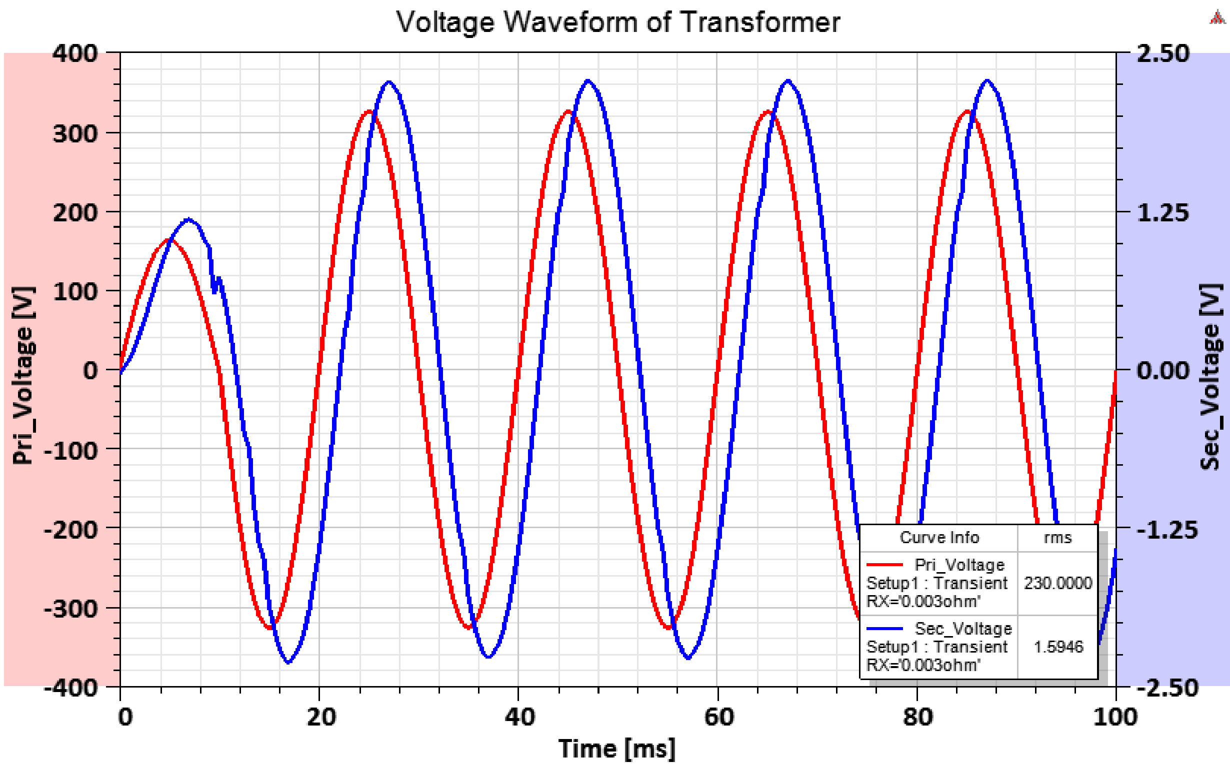

Figure 5.7 Voltage Waveform of the Transformer

The figure 5.7 shows input primary voltage and induced secondary voltage waveform of the transformer. From the figure initially there is transient in secondary voltage which is induced then it becomes stable after some time. The primary voltage is 230V which can been seen in the graph constantly flows in transformer. The induced voltage is close to analytical calculation because the conductor size was increased to with held high current output so the induced voltage is lower than analytical design calculation.

The figure 5.8 shows primary current and induced secondary current waveform of the transformer. The current induced in the secondary winding is 504A which can provide the power supply to circuit breaker in the load side. The current induced is higher than analytical design calculation but it is negligible so the transformer which is designed can works fine as for laboratory condition. The transformer with high current output as per analytical calculation that induced can be seen from the graph below.

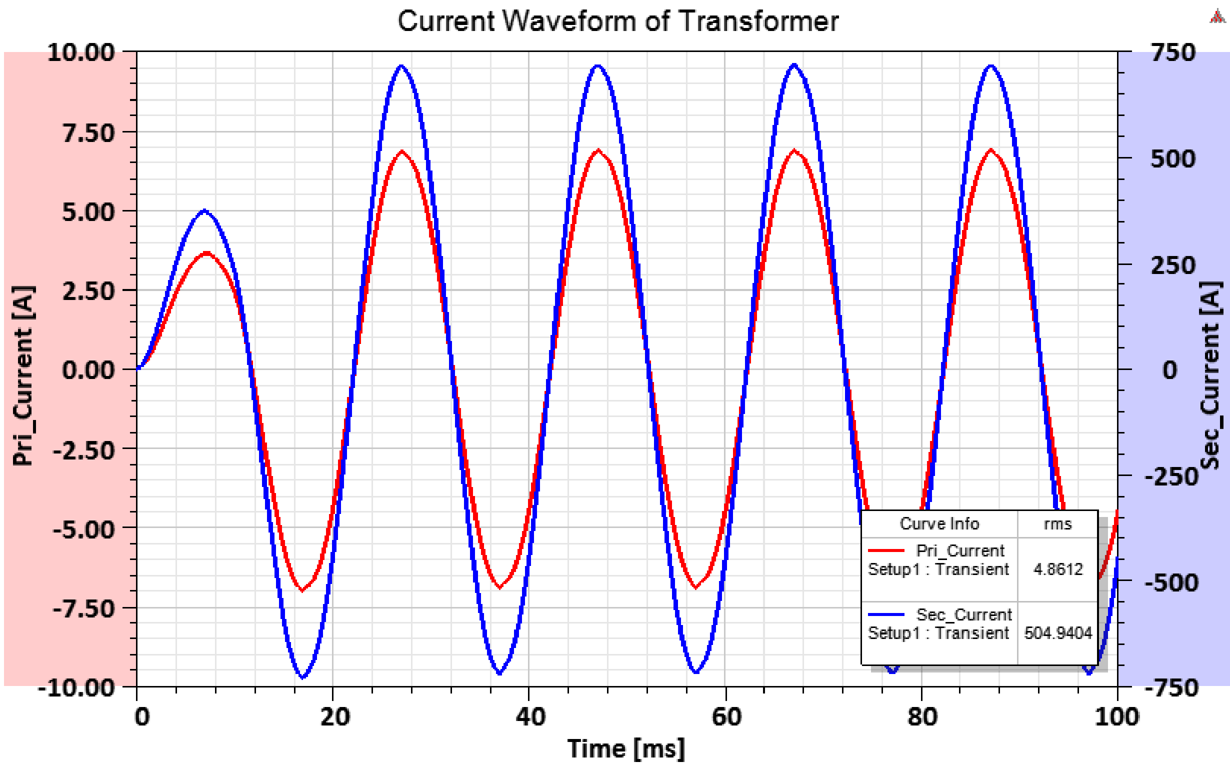

Figure 5.8 Current Waveform of the Transformer

The figure 5.9 shows the current density of the secondary winding of the transformer. The current density is slightly higher than analytical calculation due to increase in the width of the conductor.

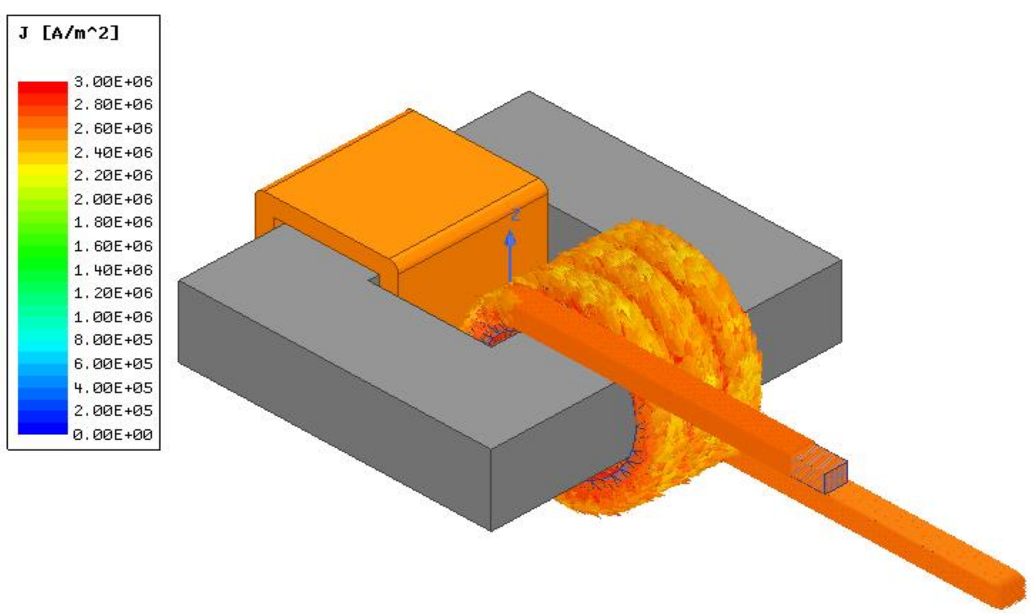

Figure 5.9 Current Density of Secondary winding

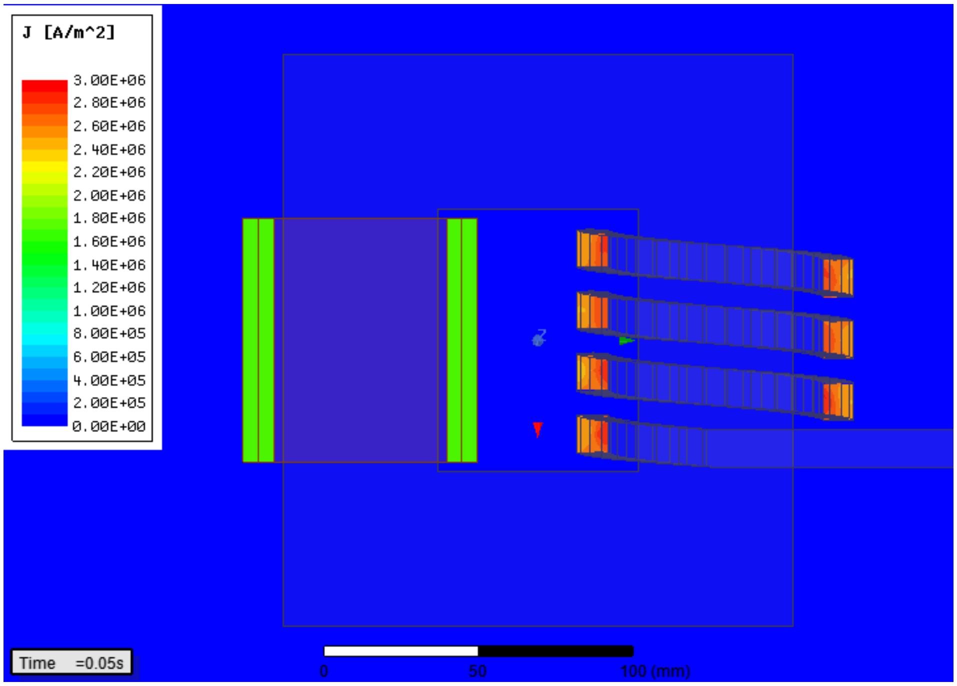

Figure 5.10 Current Density of the Transformer

The figure 5.10 shows the current density of the primary winding and the secondary winding of the transformer.

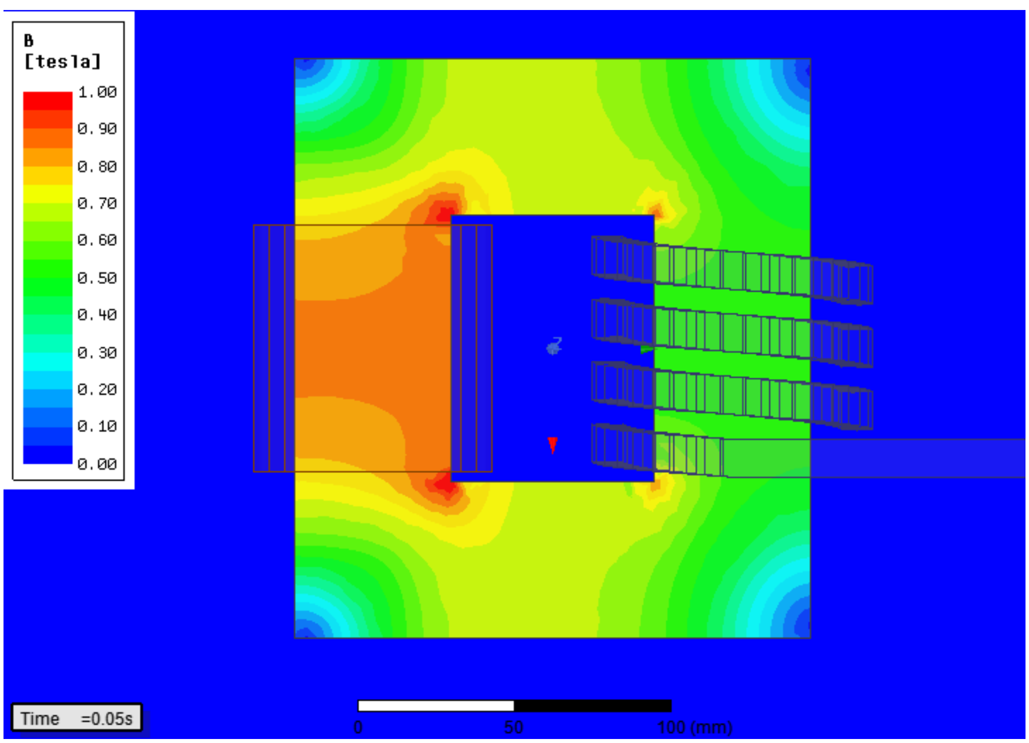

Figure 5.11 Flux density of the Transformer

The figure 5.11 shows the magnetic flux density of the transformer and the figure 5.12 shows magnetic field strength in the surrounding air. The flux density of the transformer is lower than calculate value but it is negligible. It will not affect the output of the transformer as verified in current waveform of the transformer. As the magnetic field strength decrease as per distance from the coils as seen in the figure.

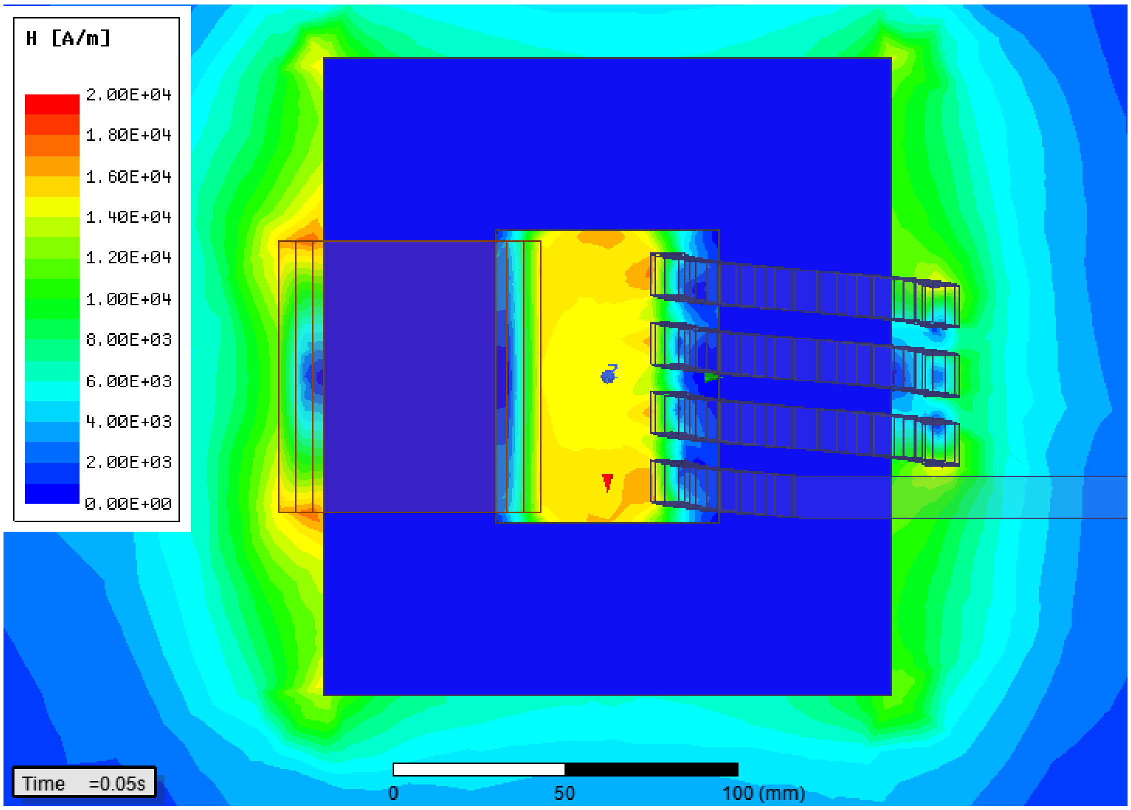

Figure 5.12 H Field in Surrounding Air

CHAPTER 6

REGULATION METHOD

6.1 VOLTAGE DROP

The transformer provides the supply to circuit breaker in the load side which will be smooth until there is temperature rise in surrounding. The transformer which is designed will work normally in the room temperature but there is always temperature rises due to heat dissipated from transformer and also from other equipments in the laboratory. As the temperature rise, it will change the room temperature which causes some changes in transformer. The output of the transformer will be affected by rise in temperature which cause power losses then the transformer cannot provide adequate supply to circuit breaker in the load side. Then the system cannot work properly which causes failure. The temperature rise mainly causes increase in resistance that cause voltage drop and power losses.

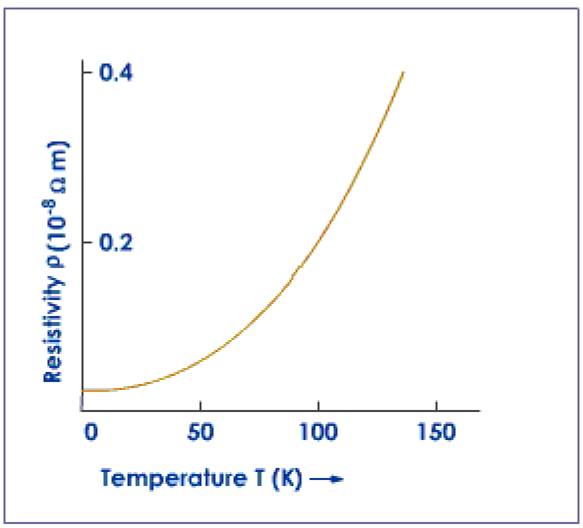

Figure 6.1 Relation between Resistance and Temperature

The temperature dependence of resistivity can only be explained with the help of quantum mechanics. When the temperature increases the vibrations of the metal ions in the lattice structure increases. The atoms starts to vibrate with higher amplitude. These vibrations in turn causes frequent collisions between the free electrons and the other electrons. Each collision drain out some energy of the free electrons and causing them unable to move. Thus it restricts the movement of the delocalized electrons. When the collision happens the drift velocity of the electrons decreases. This means that the resistivity of the metal increases and thus current flow in the metal is decreased. The resistivity increases means that the conductivity of the material decreases.

Thus the resistivity of the material can be described as,

$$\rho t = \rho 0 \left[1 + \alpha \left(T - T0\right)\right] \quad ....(6.1)$$

Where,

ρt = Resistance of the conductor at temperature T.

$\rho 0$ = Resistance of the conductor at temperature T0.

α = Temperature coefficient of temperature of material of conductor.

T0 = Room temperature.

T = Conductor temperature.

6.2 COMPENSATION METHOD

A system is proposed in order to compensate the voltage drop, as power losses happened due to increase in resistance which is caused by rise in temperature. A compensation transformer is introduced for compensation method. The output current in load side of the transformer is constantly monitored with the help of ammeter.

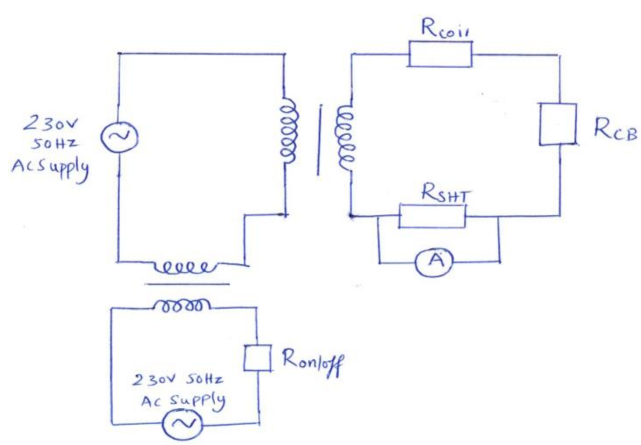

Figure 6.2 Circuit Diagram for Regulation method

The changes in output current is measured across the shunt resistor by the ammeter as per the figure 6.2. The compensation transformer is connected in series with the primary side of main transformer. When output current drops below a certain value, the compensation transformer turned on to compensate the losses. When temperature gradually rises as time goes on, the resistance of the conductor also increase which resists the constant current flow in load side of the transformer that causes the power losses.

As compensation transformer supplies the power required which is constantly turned on and off by monitoring the ammeter that is tedious process to user. In order for remove the tedious process for user, PID controller is connected between ammeter and compensation transformer turn on/off switch. The current measured in the ammeter will connected as input for PID controller. In the PID controller, the input is compared to constant predefined value of actual output before the temperature rise. If the input is lower than certain value, the PID controller decreases the resistance across the compensation transformer which increase the power required. If the input increase or decrease it will directly influence the resistance across the compensation transformer.

6.3 FEM DESIGN

The transformer and circuit for regulation method are designed with help of ANSYS Maxwell simulation software. The main transformer is designed in 2D model to analysis and to simulate the working model of the system. The circuit of regulation method is constructed and designed as per analytical calculation. The magnetic core of main transformer is designed first and then primary conductors and secondary conductors are also designed.

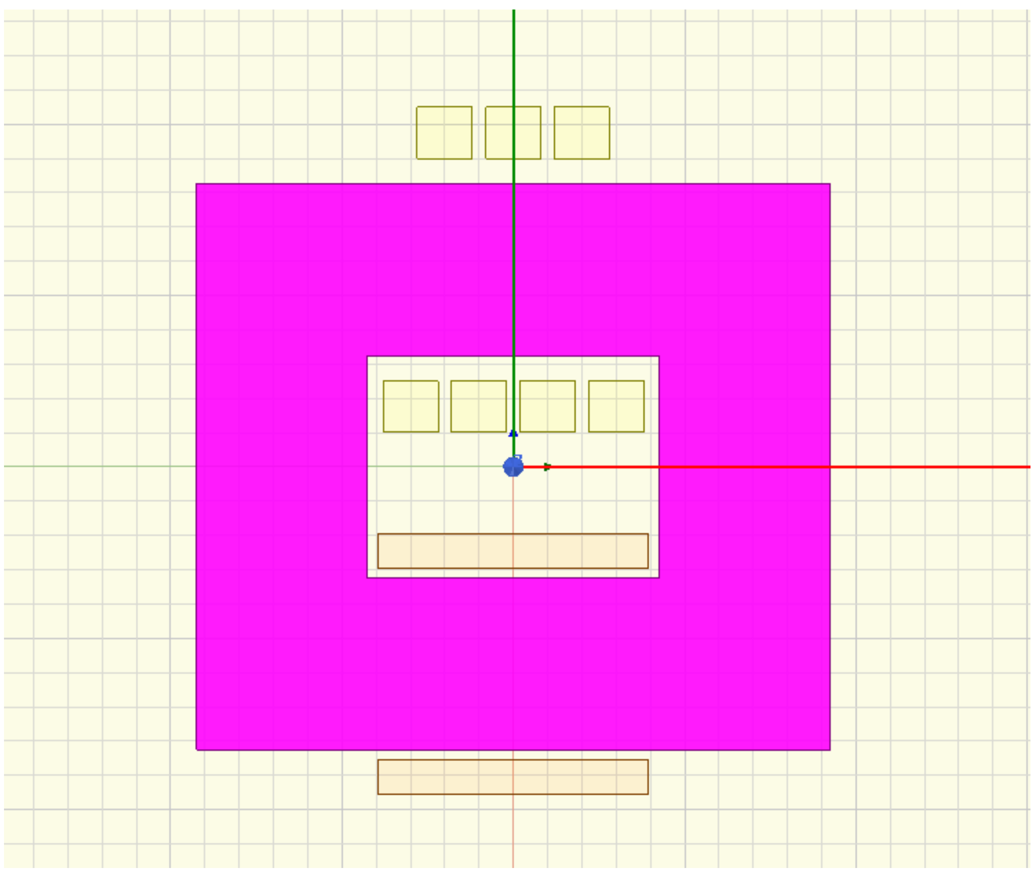

Figure 6.3 2D Model of Core of the Transformer

The figure 6.3 highlights 2D model of the magnetic core of the transformer. The material of magnetic core is steel for high saturation flux density.

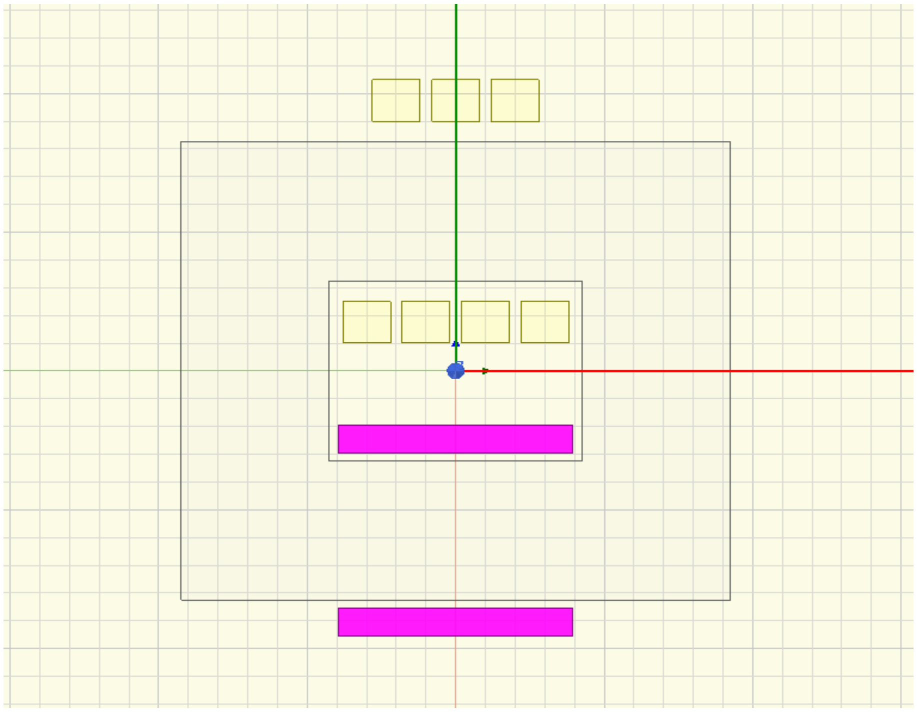

Figure 6.4 2D Model of Primary winding of the Transformer

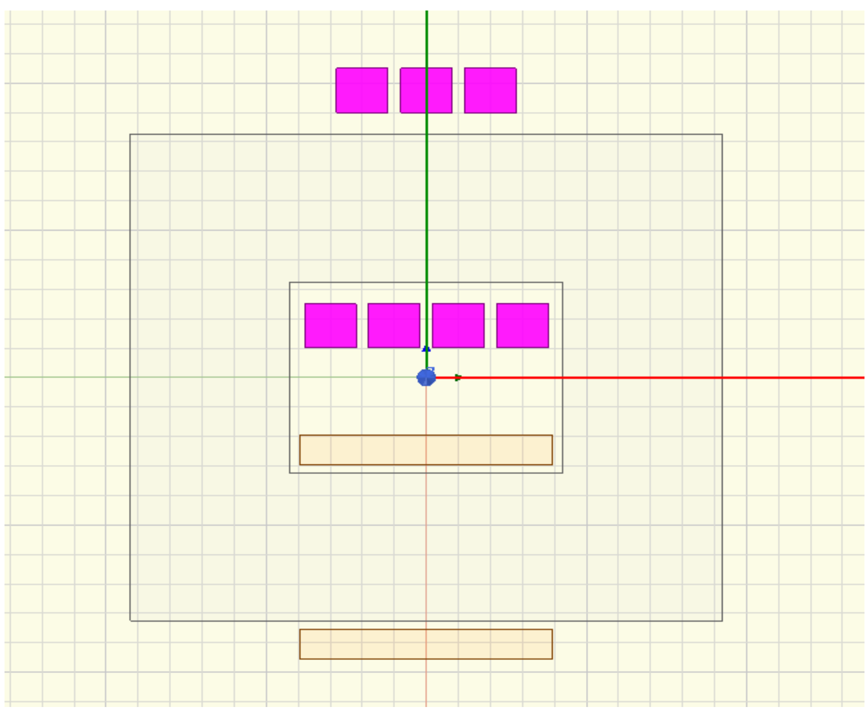

Figure 6.5 2D Model of Secondary winding of the Transformer

The figure 6.4 highlights the design of 2D model of the primary winding of transformer. The design looks like rectangular bar but the coils are wounded in that shape. The figure 6.5 highlights the design of 2D FEM model of the secondary winding of transformer. The design shows the numbers of turns. The material is copper for both of the windings. The figure 6.7 & 6.8 shows conductors present inside both of the windings as per the design.

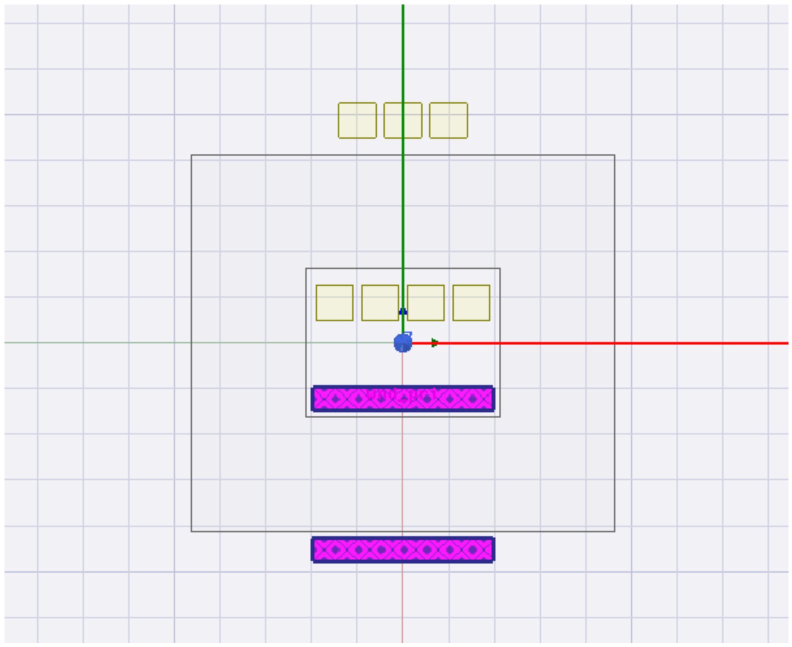

Figure 6.6 2D Model of Primary Conductors of the Transformer

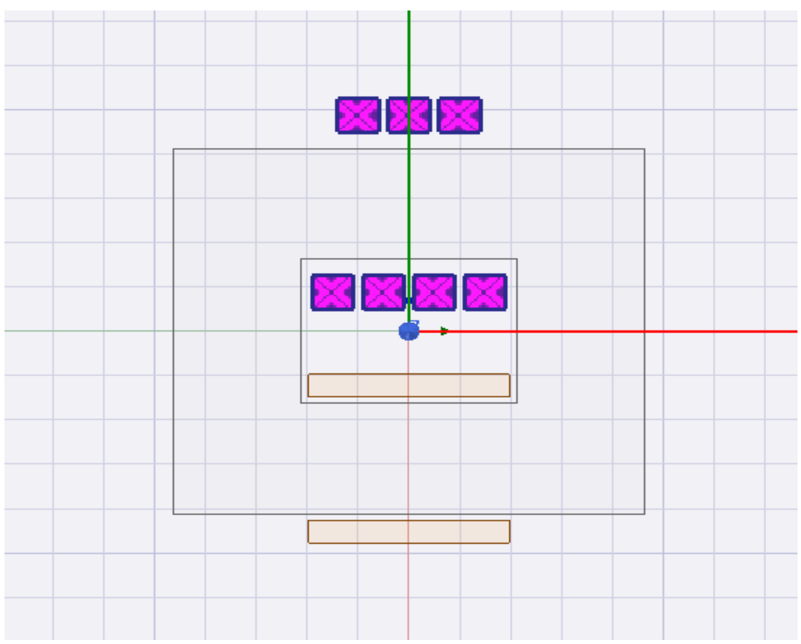

Figure 6.7 2D Model of Secondary Conductors of the Transformer

6.4 SCHEMATIC CIRCUIT OF REGULATION METHOD

The schematic circuit of the regulation method is designed with help of ANSYS Maxwell simulation software. The power supply of 230V 50Hz is connected to main transformer and circuit breaker is connected in load side of the transformer. The ammeter is connected to shunt resistor to measure the output current. PID controller is connected between ammeter and compensation transformer.

The rms value of current measured in the ammeter will send as input for PID controller. In the PID controller, the input is compared to constant predefined value of actual output as shown in figure 6.8. If the input is lower than certain value, the PID controller decreases the resistance across the compensation transformer which increase the power required.

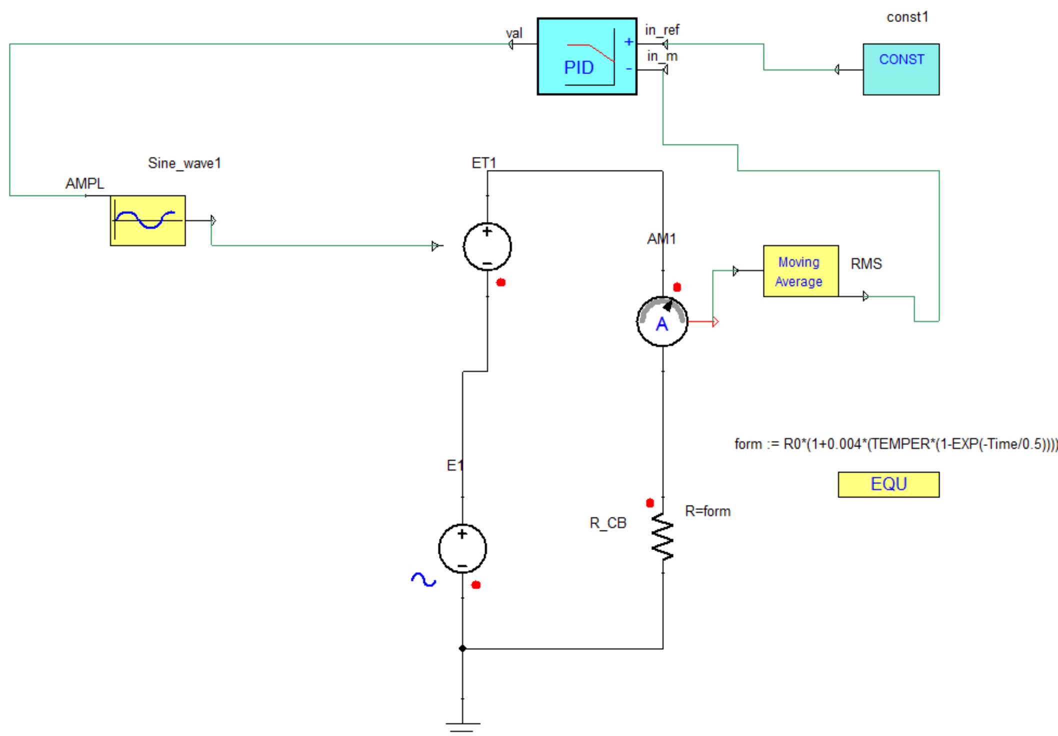

Figure 6.8 Schematic Circuit of Regulation method

The system runs as per design until the temperature rises that cause rise in resistance. The current decrease that cause power loss then PID controller takes control. The PID controller then stabilize the current flows which minimize the power loss.

The Figure 6.9 shows the rms value of the output current which measured by ammeter that send as input to PID controller. The average value of current is 490A as per graph where you can see that there is initial surge due to temperature rise. Then it got stabilized.

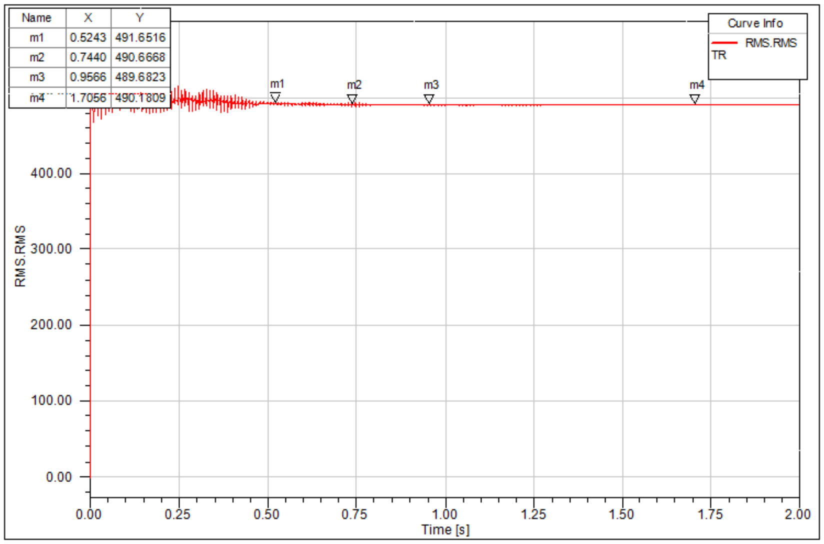

Figure 6.9 RMS value of Output Current

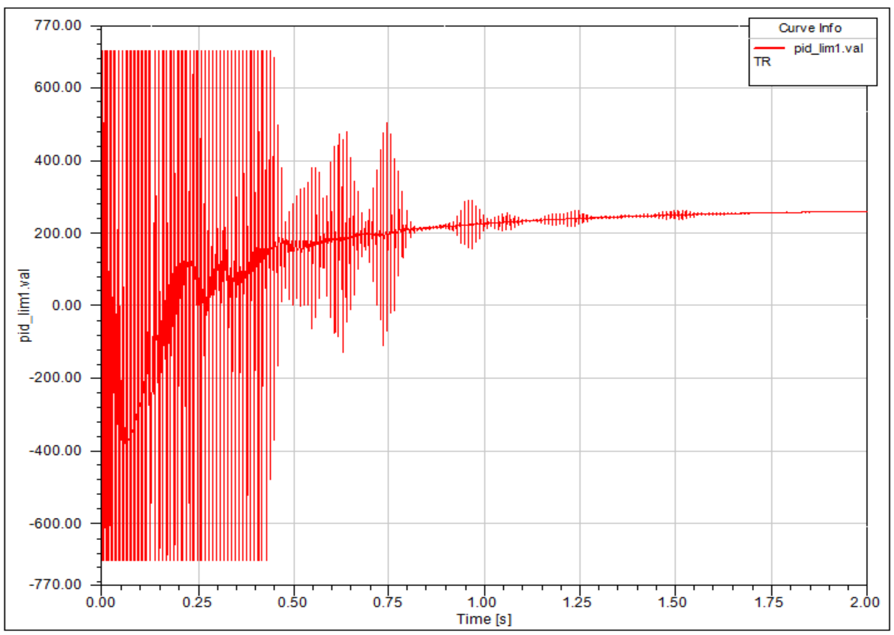

Figure 6.10 PID Controller graph

The Figure 6.10 shows the graph of PID controller. The average value of current is send into PID controller as input and compared with constant value. The figure 6.11 shows graph of emf of the transformer where you can see that there is initial surge due to temperature rise. Then it got stabilized.

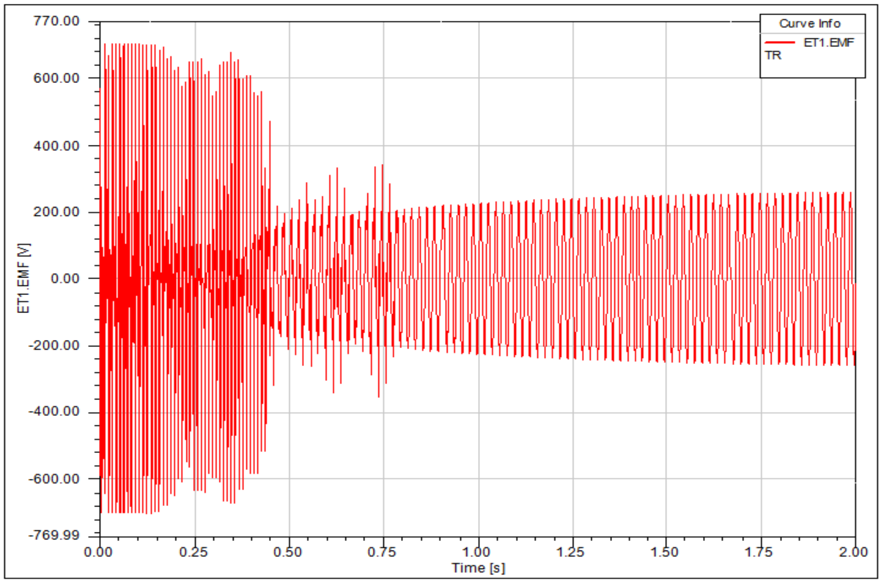

Figure 6.11 EMF in the Transformer

6.5 RESULTS OF REGULATION METHOD

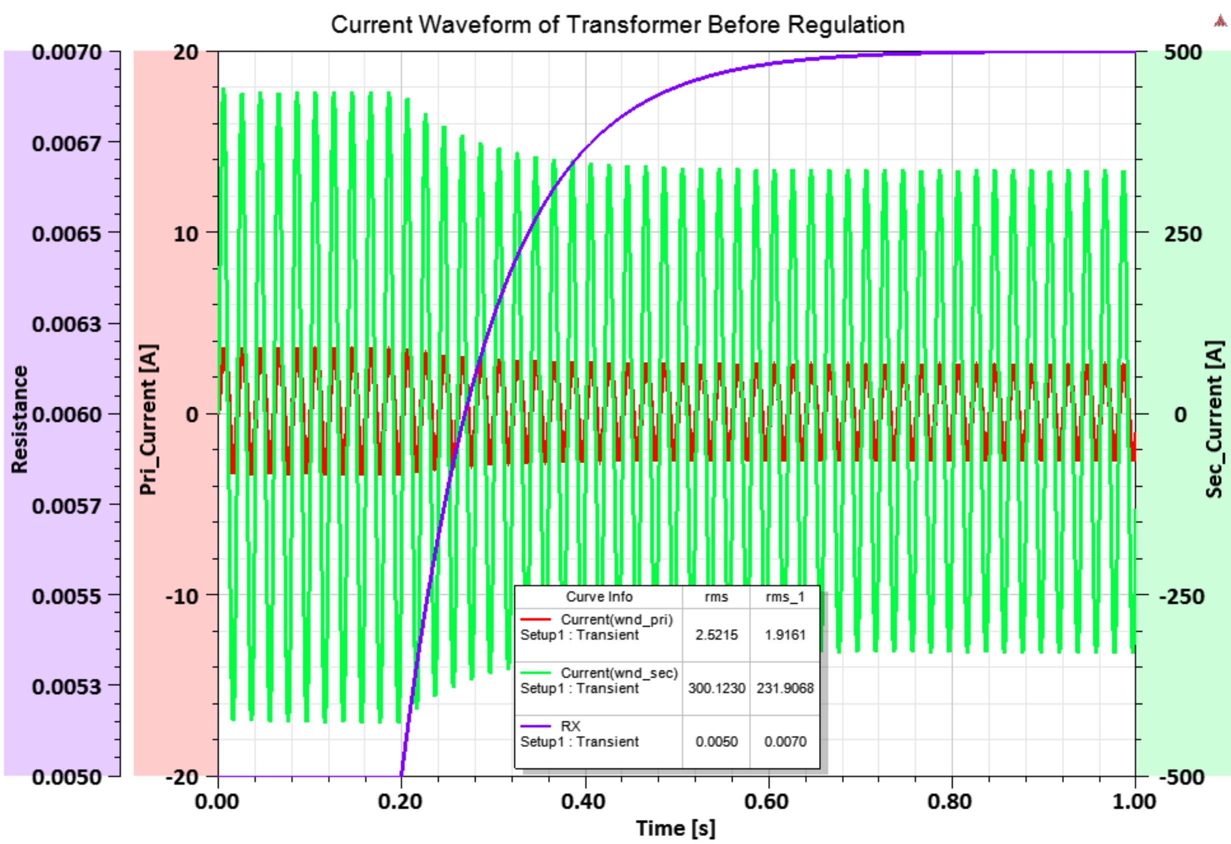

Figure 6.12 Current Waveform of the Transformer before Regulation

The Figure 6.12 shows output current of the main transformer before the regulation. This graph represents the transformer output where the compensation transformer and PID controller did not connected to main transformer. As the regulation system not connected so there is no regulation method to recover the power losses. Then the transformer cannot produce enough supply to circuit breaker in the load side after the temperature rise.

In real time, rise of temperature takes more than 120 seconds as it slowly increase but to make it in the simulation, the analysis will take much time and the waveform cannot be commuted in normal means so temperature starts to increase at 0.2s and it starts to stabilize after 0.6s in the simulation. As in graph the output current start to decrease as resistance increase at 0.2s due to temperature rise. When the temperature rise to maximum temperature more than 70A decreased as per rms value in graph. This shows there is need of a regulation system or else the transformer output cannot be stabilized when there is temperature rise.

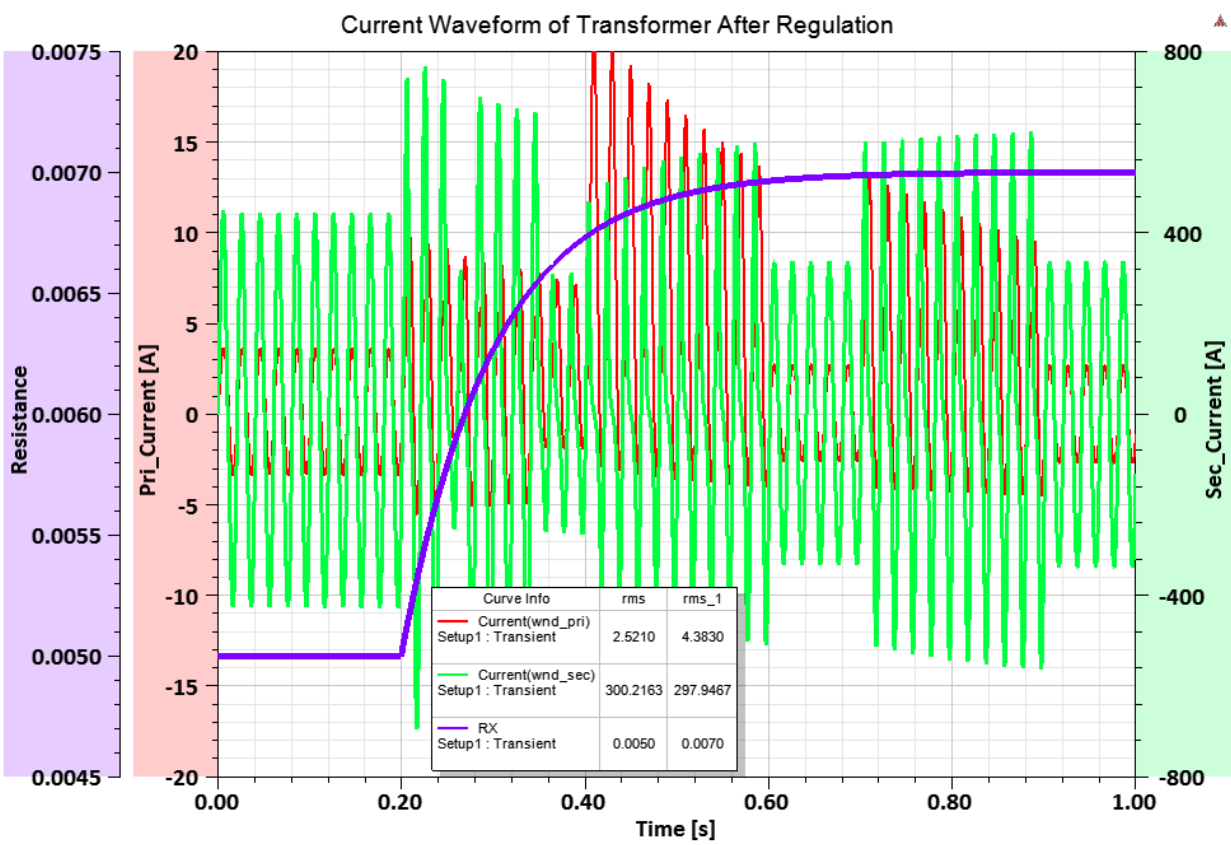

Figure 6.13 Current Waveform of the Transformer after Regulation

The Figure 6.13 shows output current of the main transformer after the regulation. This graph represents the transformer output where the compensation transformer and PID controller connected to main transformer. As the temperature starts to rise at 0.2s, PID controller in the regulation system starts to stabilize the output of transformer by decreasing or increasing the resistance in the compensation transformer. When the temperature rise from 0.2s to peak after

0.6s,the input and output cycles of transformer varies in order to provide stable supply to load can be seen from the graph. The rms value of the output current are same both from beginning where temperature not start rise and after temperature reaches the peak because of the regulation system. From the graph we can see that in the simulation, the regulation system works perfectly to maintain output of the transformer and reduce the voltage drop in case of temperature rise.

CHAPTER 7

CONCLUSION

The theoretical background and types of the transformer has explained. A single phase transformer with high current output according to requirements of laboratory measurement of electrical apparatus has developed with analytical design calculation. The analytic design of transformer using FEM simulator has checked in Ansys Maxwell simulation software and a solution for voltage drop because of temperature rise with help of analytical calculations in laboratory situations has found. The selected compensation method has been applied into design of transformer and checked with help of Ansys Maxwell simulation software.

This regulation system helps to maintain the output power that can be supplied to load during rise of the temperature. When there is no regulation system, the power loss and voltage drop in the transformer is higher which can fail to maintain the current flow in load. The equipments which are connected cannot work properly sometimes causes damage because of sensitivity. The regulation system helps to protect the equipments in laboratory. The flux density distributed in transformer of 3D FEM design and the magnetic field strength in surrounding air has pictured with the help of simulation software. The voltage and current of transformer of 3D FEM design are graphed. The changes in output current with and without the regulation method during rise of the temperature are monitored and graphed which help to understand the uses of the regulation method. In future, advanced PID controller can be used to provide support to compensation transformer which can provide minimum voltage drop and power loss.

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